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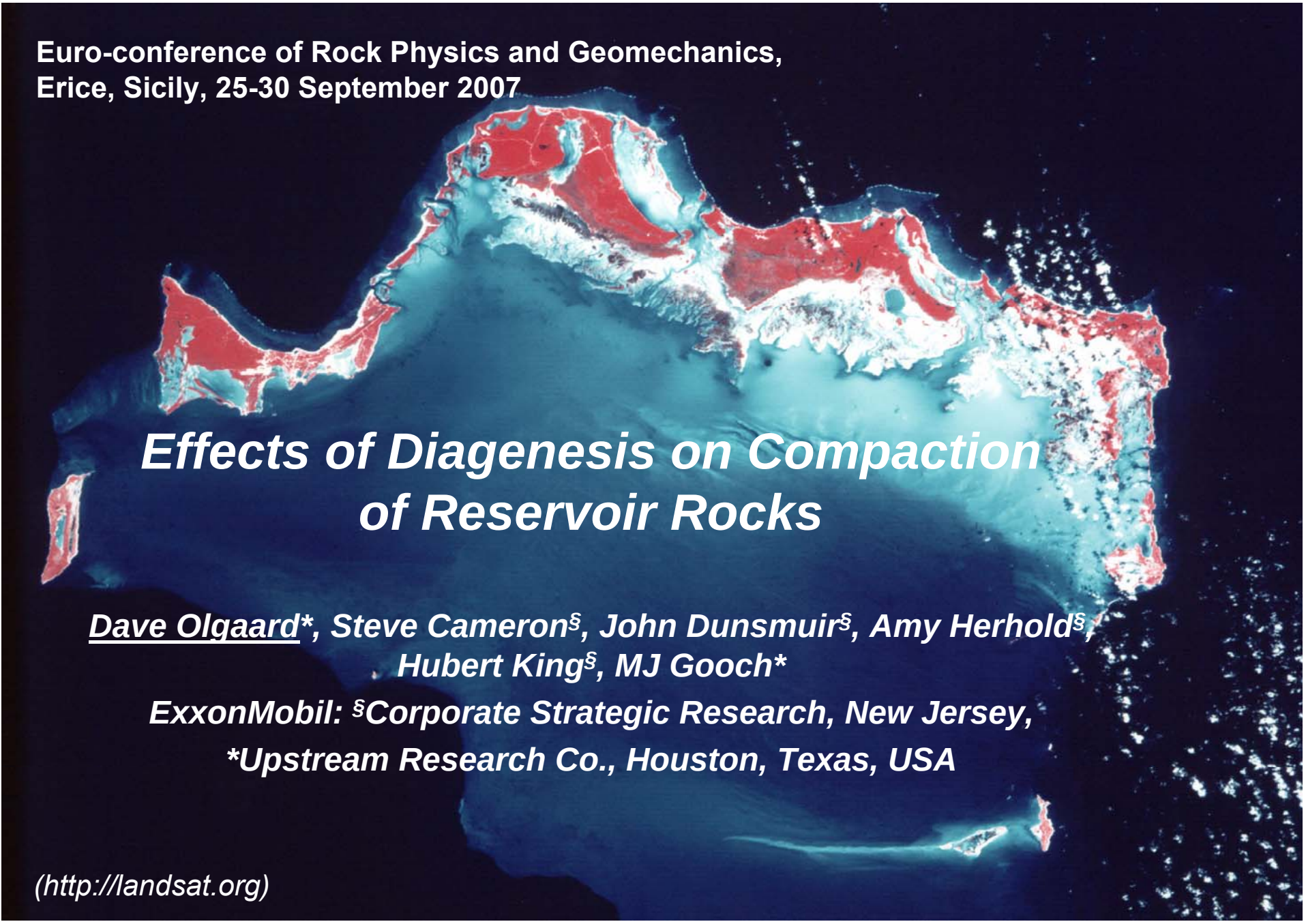
Euro-conference of Rock Physics and Geomechanics,
Erice, Sicily, 25-30 September 2007



Effects of Diagenesis on Compaction of Reservoir Rocks

Dave Olgaard*, Steve Cameron§, John Dunsmuir§, Amy Herhold§, Hubert King§, MJ Gooch

ExxonMobil: §Corporate Strategic Research, New Jersey,

****Upstream Research Co., Houston, Texas, USA***

(http://landsat.org)

Why worry about compaction?

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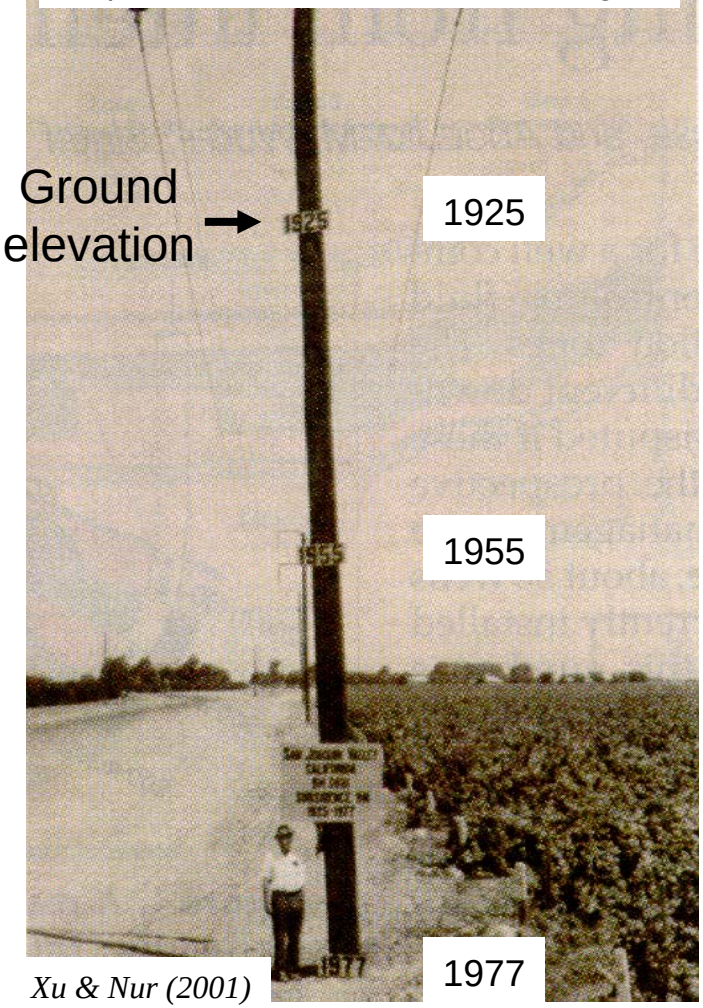
Bakersfield, California
Ground water withdrawal
9m / 50 yrs
Oil production-induced rates can be higher!

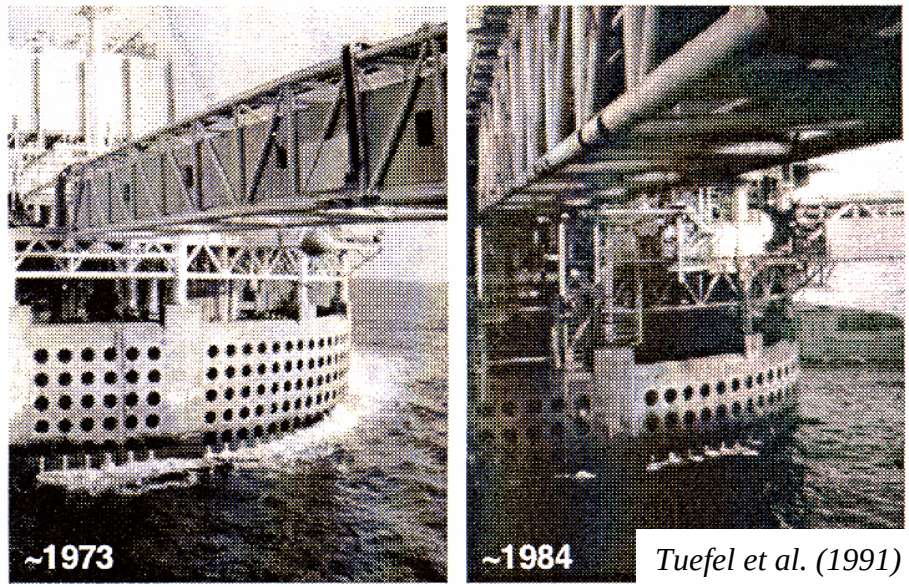


Xu & Nur (2001)

Porous silica (diatomite) reservoirs

Porous carbonate reservoirs

Ekofisk, North Sea

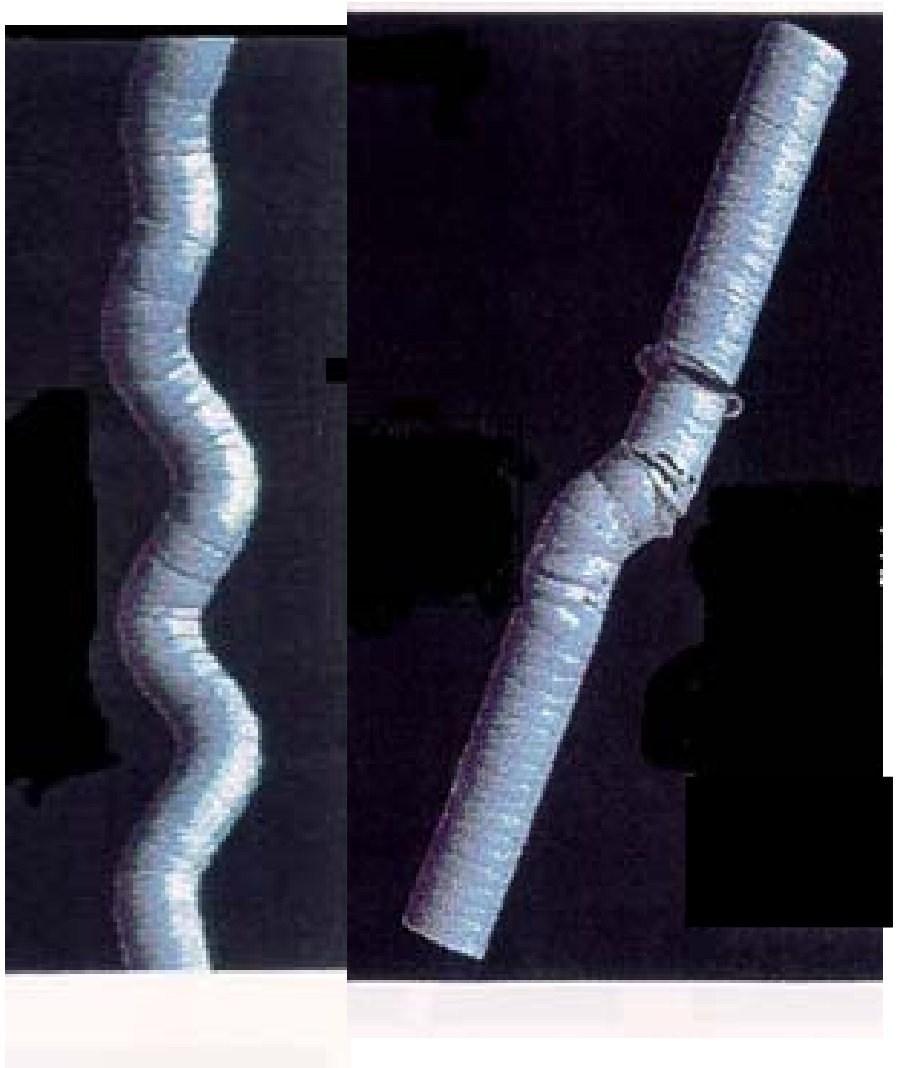


Tuefel et al. (1991)

- **20 – 23 MPa reduction in reservoir pressure**
- **> 4 m of seafloor subsidence**
- **> US$1G to raise platform**
- **compaction + fracture perm. ⇒ extended lease, added resource**

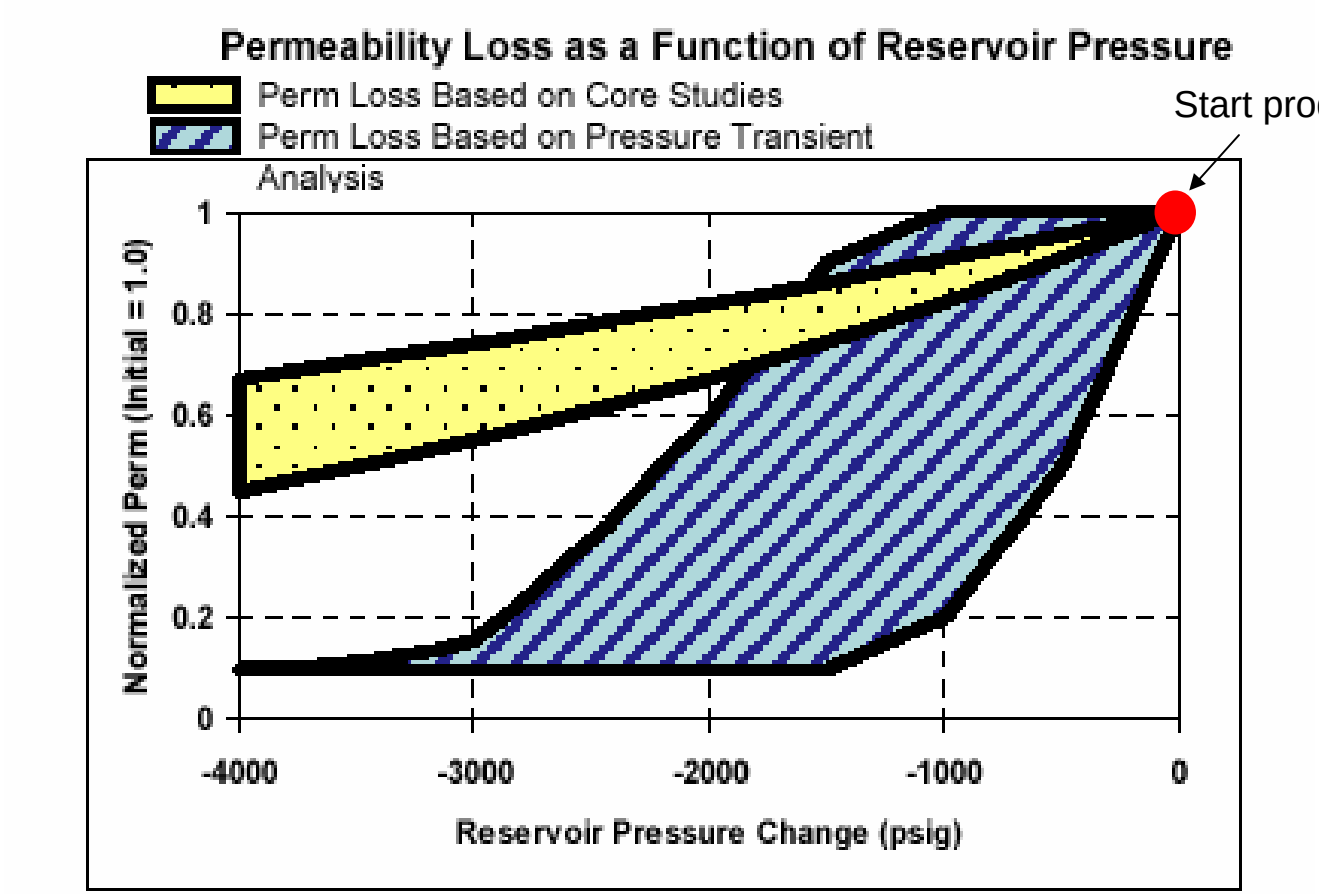
Wellbore failure

Borehole acoustic televiewer images



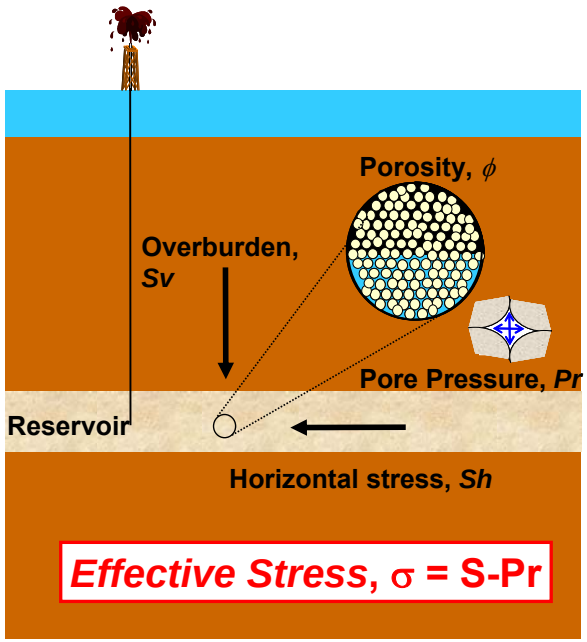
Permeability reduction by depletion

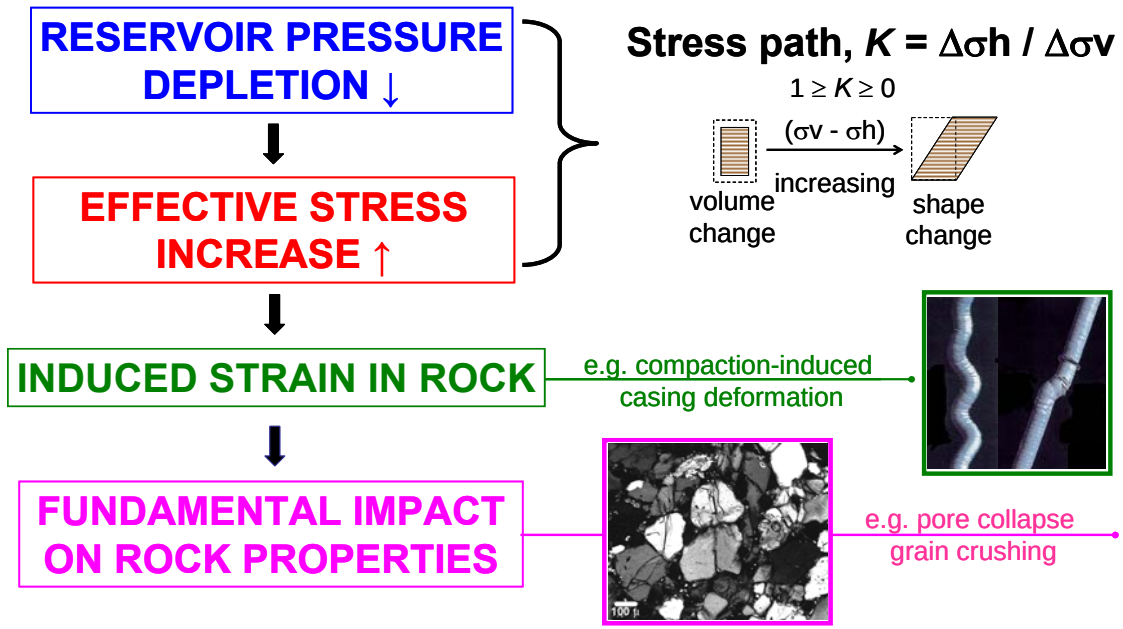
GENESIS, deepwater GOM



Chevron, SPE 84415

Basic mechanics during reservoir production





- ***Geomechanics is an essential element of the dynamic reservoir environment***

Diagenesis and Compaction

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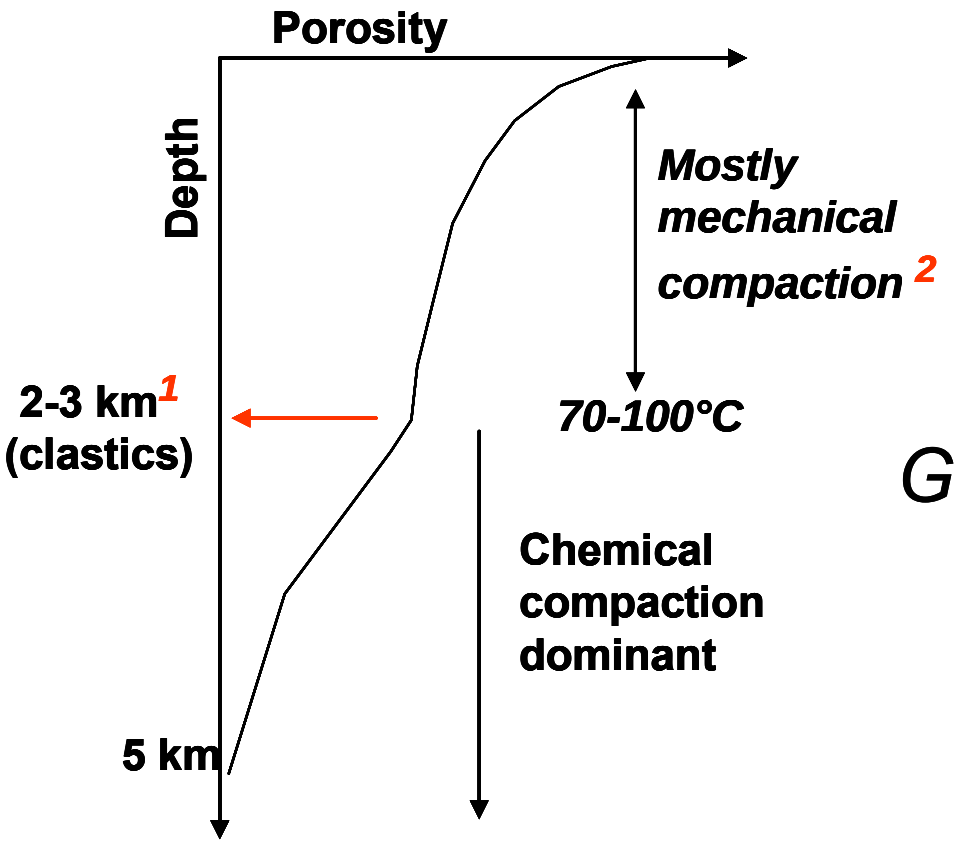
Definition: **Diagenesis – Physical and chemical changes in a sediment that convert it into a rock.** *Am. Geol. Inst.(1976)*

Outline:

- Motivation for research
- **Typical "porosity / density profiles" (mechanical and chemical effects)**
- **Current research project (emphasis on carbonates)**
  - **State-of-the-Art**
  - **Fabrication of synthetic oolitic grainstones**
  - **Compaction behavior** (porosity versus effective stress)
  - **Quantitative imaging** (X-ray microtomography)
  - **Next steps**

Reservoir Quality Prediction: porosity profiles

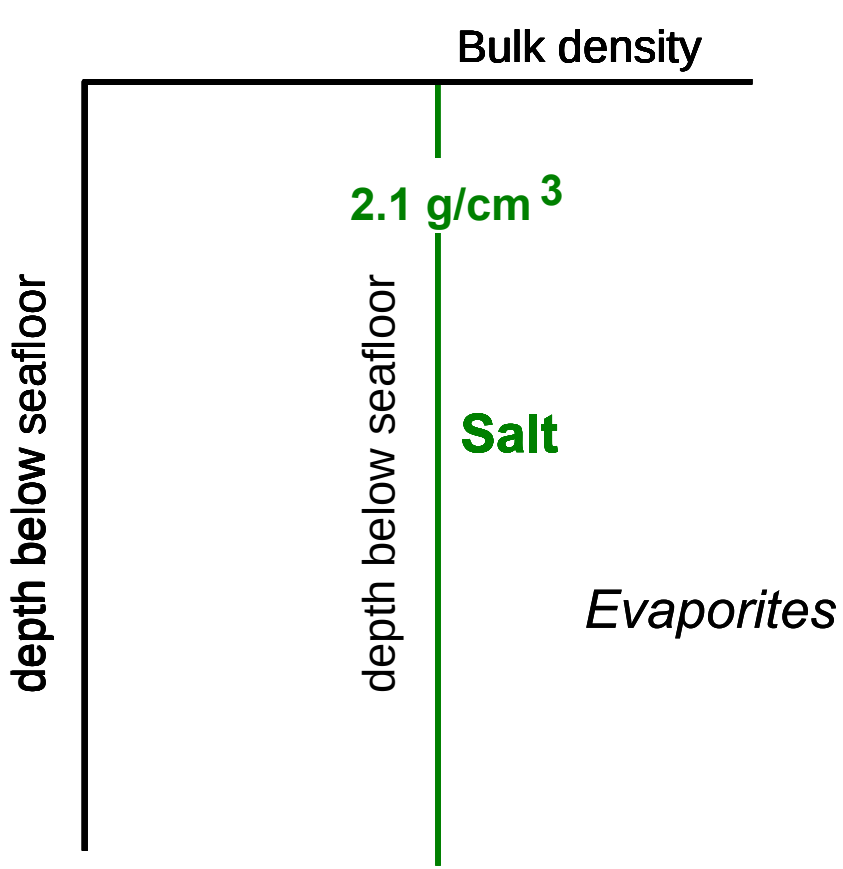


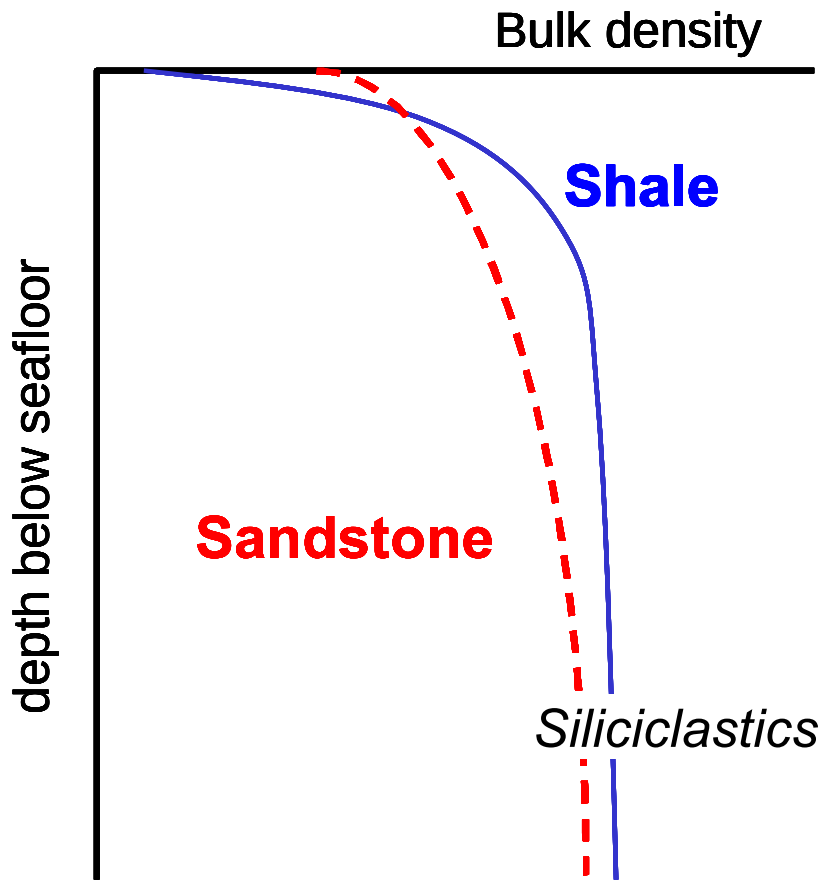
General

1 Carbonates and evaporites compact chemically at shallower depth than silicates.

2 Mineral strength: quartz & feldspar ≥ carbonates > gypsum > salt

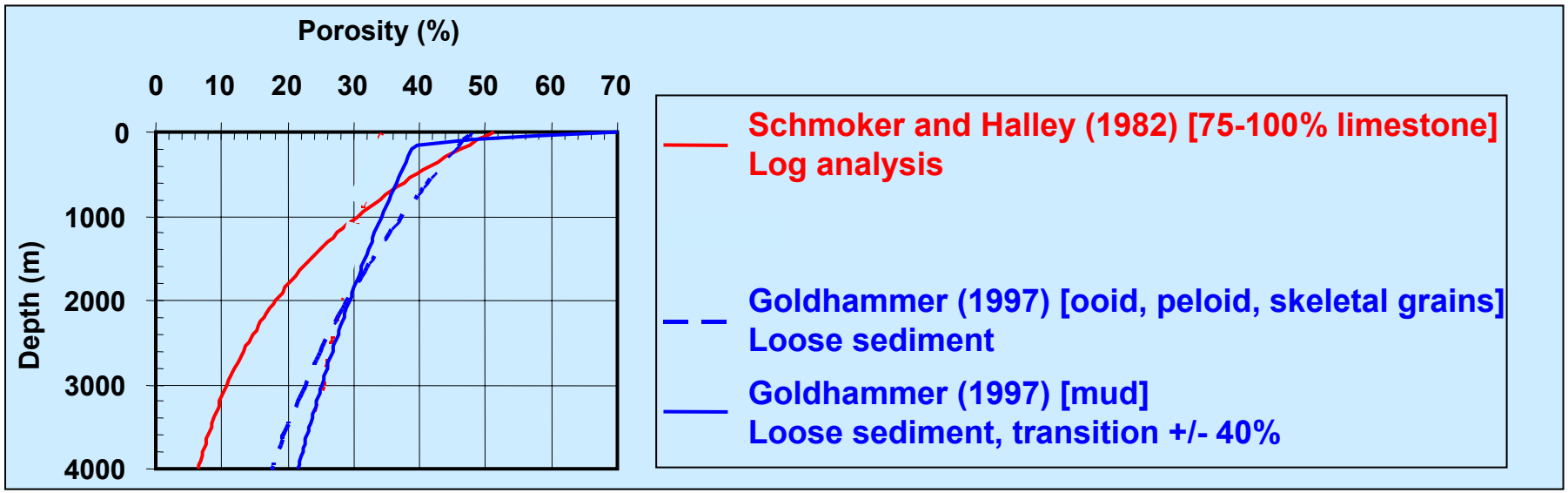
Basin Modeling: density profiles





Carbonate Compaction: Sediment Type & Alteration

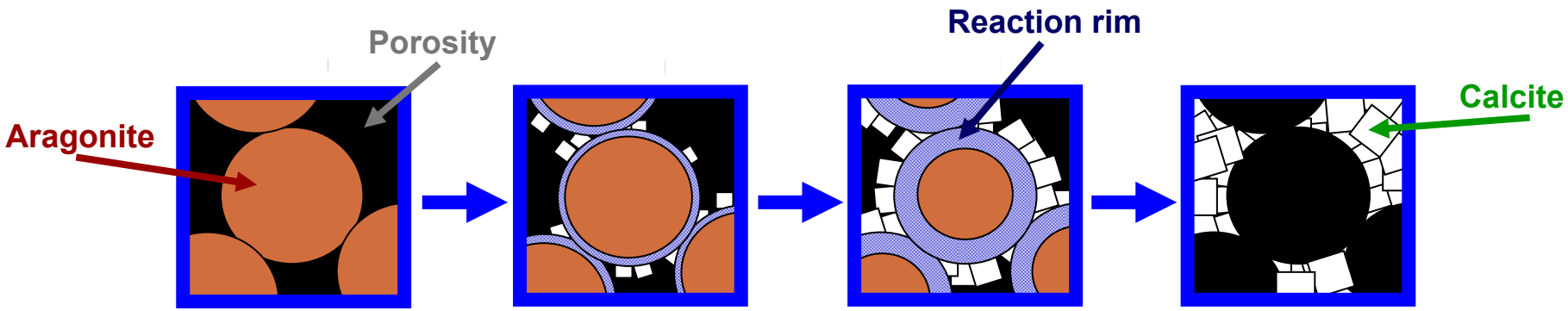
- Carbonate compaction curves:
  - Natural carbonates: variety of rock types, both mechanical and chemical alteration
  - Experimental: effects of chemical diagenesis not included in mechanical properties
- Current data predicts a wide range of outcomes – which is correct?



Need a method to predict compaction as function of sediment type and diagenetic alteration

Moldic Porosity in Ooid Grainstones

- **Marine oolites are important reservoir rocks**
  - **E.g. Ghawar Field, Saudi Arabia,** *(Flugel, 2004)*
- **Diagenesis of ooids inverts original intergranular porosity to moldic porosity**
- **Por. & perm. depend on both environment of deposition & diagenesis**



- ***Similar total porosity as original sediment, but very different permeability.***
- ***How does the inversion affect the porosity-depth curve?***

- **A-C conversion occurs in fresh water lens, only 1-2 m below sea surface**
  - ***I.e., diagenesis with little load; e.g. experimentally tractable***

- **Fabrication of moldic porosity previously established**
  - ***Challenge: Make samples large enough for geomechanics tests***

Research: *Determine Effects of Diagenesis on Compaction of Synthetic Oolitic Grainstones*

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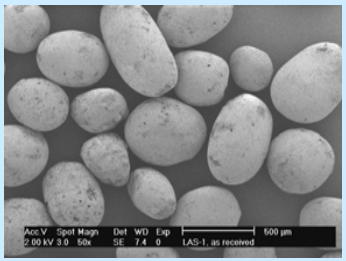
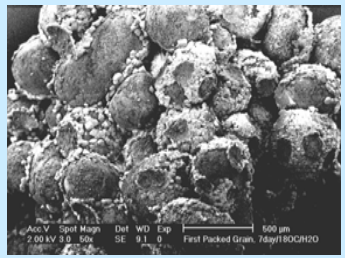
Natural ooid sand

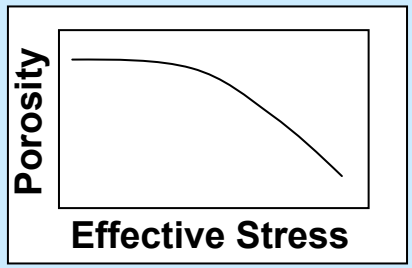


Heat to accelerate kinetics

Create diagenetically-altered rocks



Acquire compaction curves from uniaxial strain experiments



Follow microstructure with X-ray microtomography + thin section imaging

- **Synthetic rocks decouple effects**
  - ***Adjust kinetics (t/T) to control diagenesis***
  - ***Study effect of diagenetic environment without overprinting***
  - ***Focus on matrix rather than vugs present in natural samples***

Natural grainstone *(U. Miami)*

Synthetic grainstone *(current)*

Samples Fabricated in Autoclave

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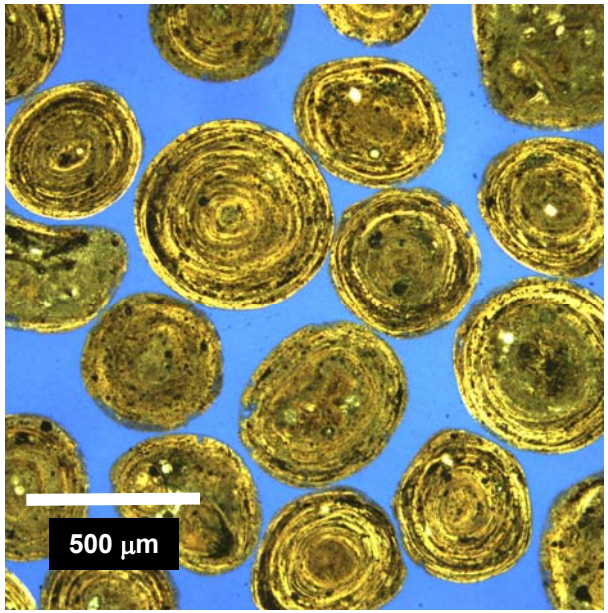
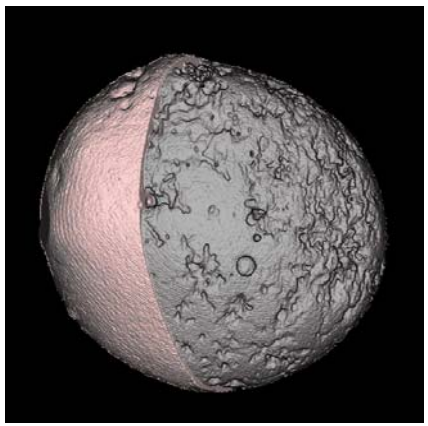
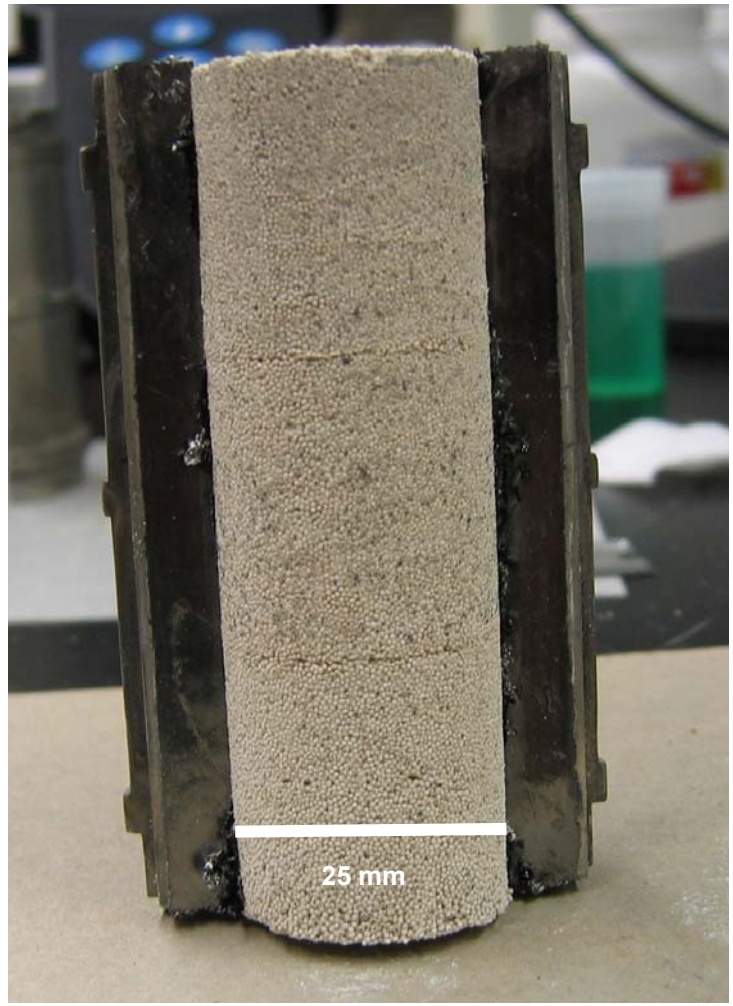
Aragonite Ooids



X-ray microtomography





Typical Mechanical Strength Tests

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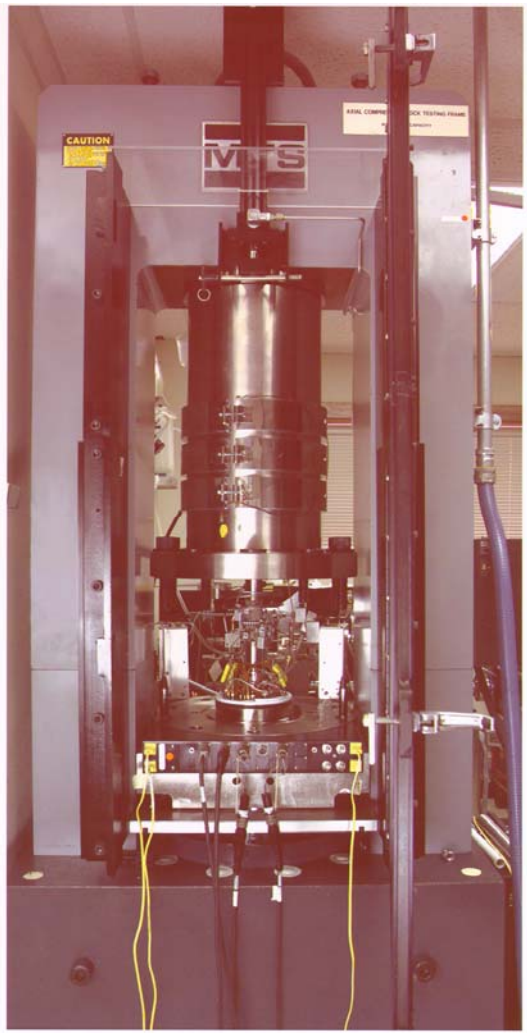
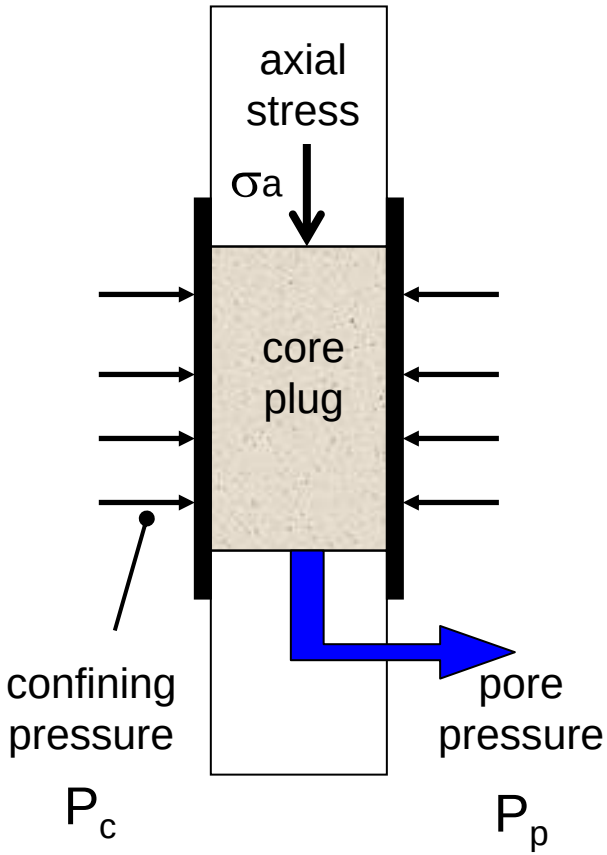
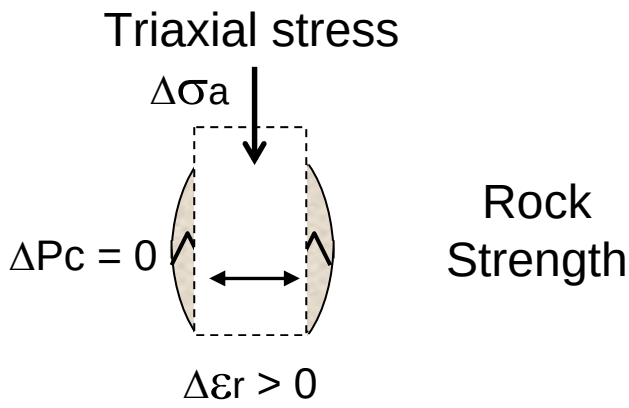
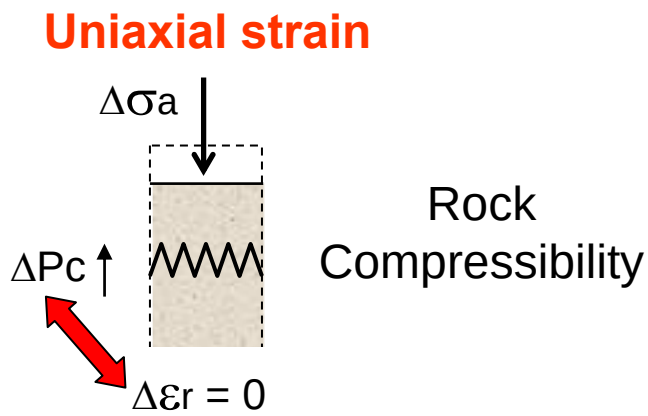
Triaxial Load Frame

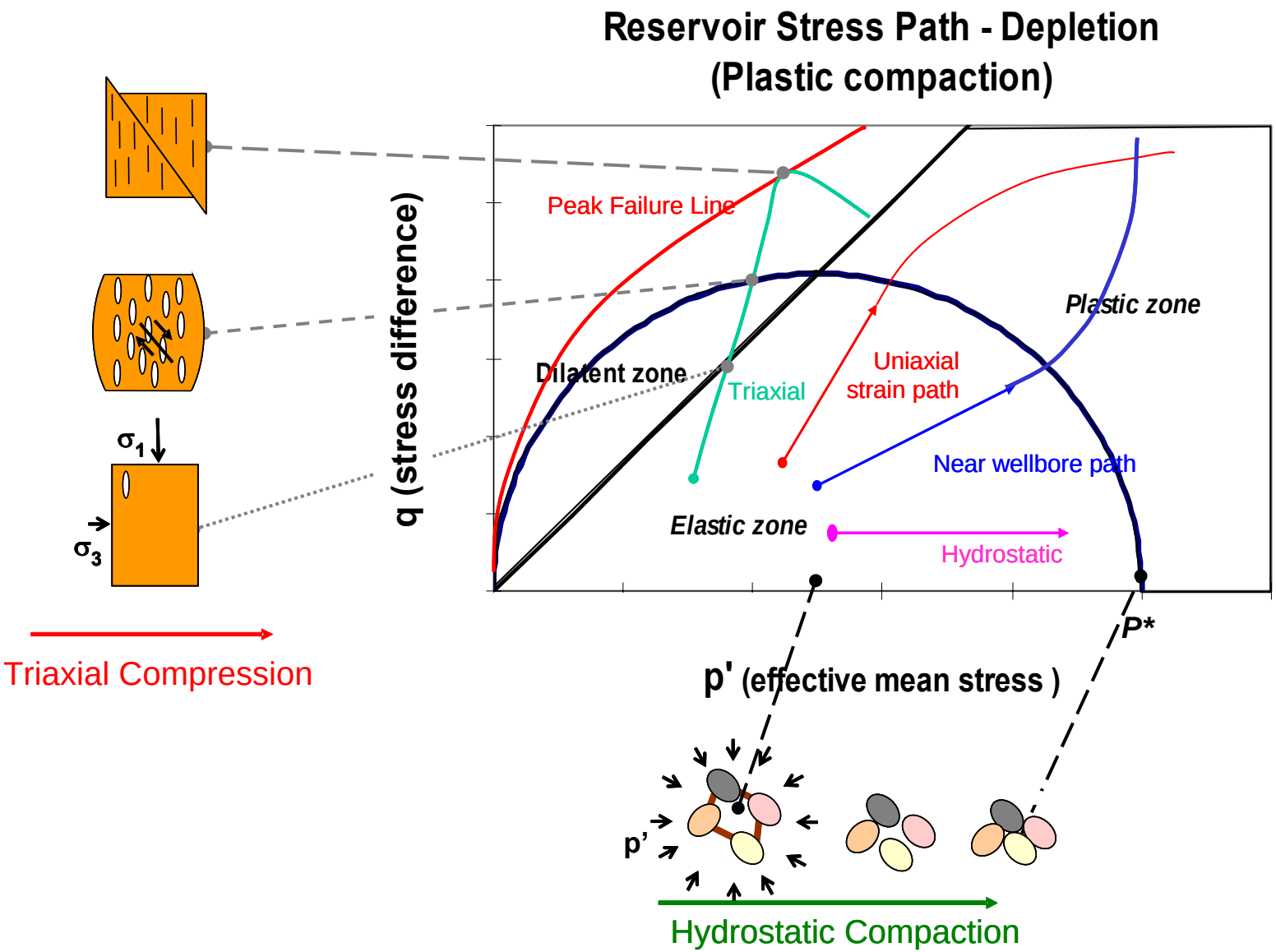






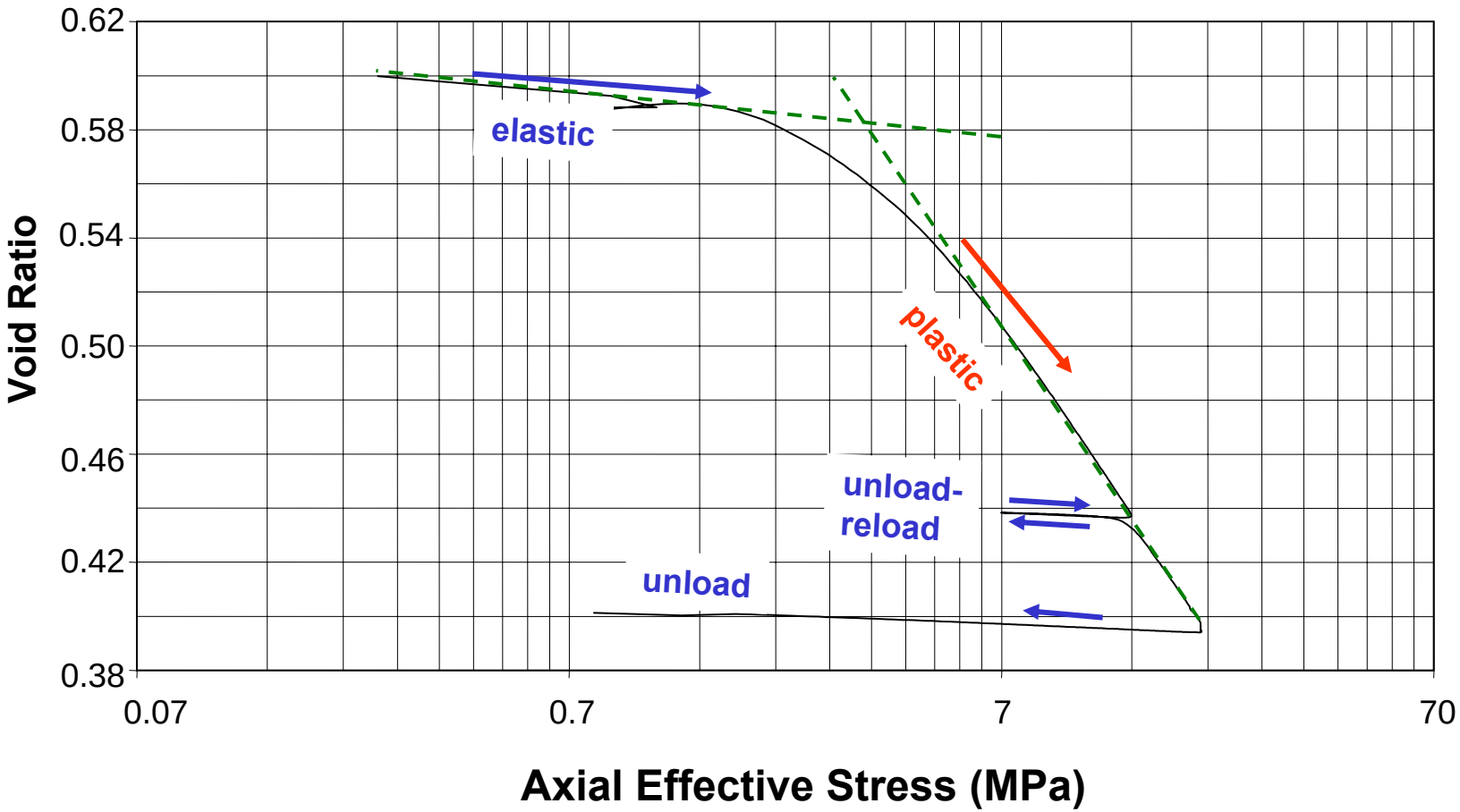


Typical Stress Paths



Typical drained uniaxial strain test

Unconsolidated sediment



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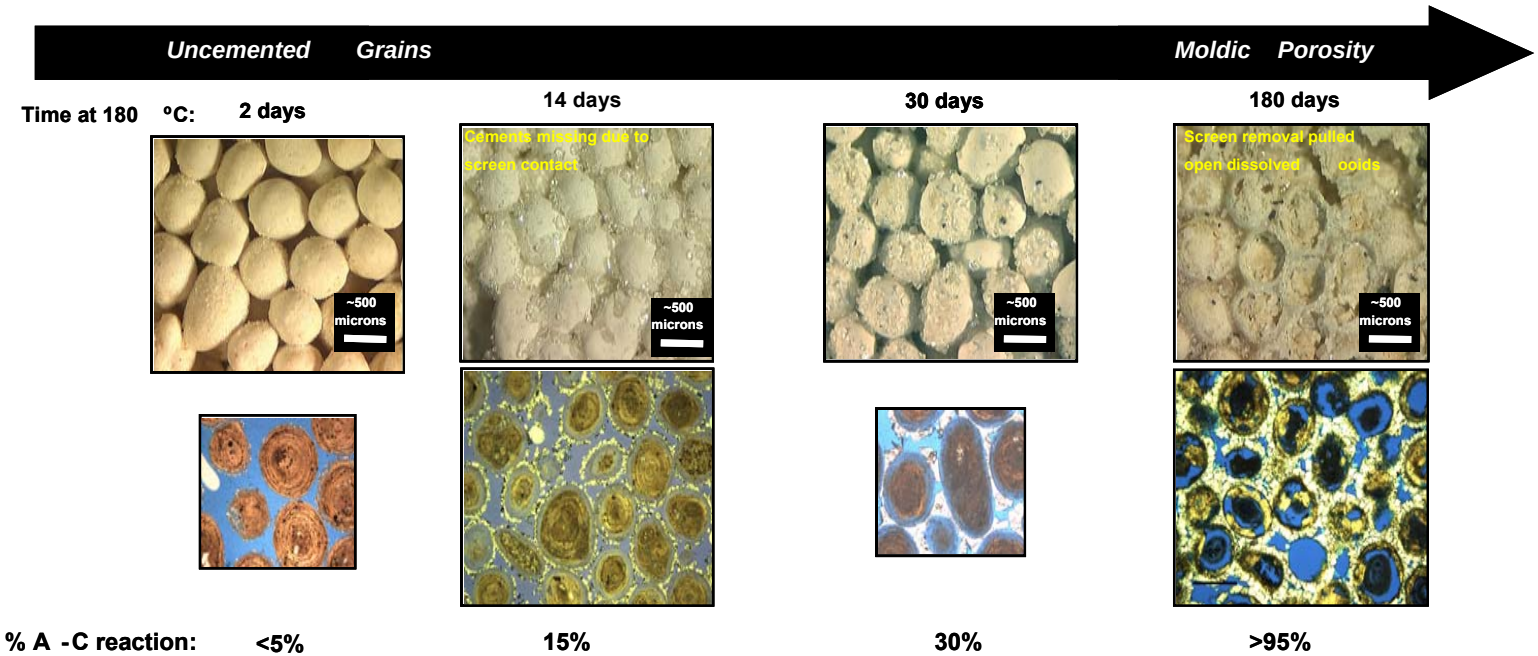
Fabricating synthetic oolitic grainstones

Laboratory - Simulated Diagenesis



Lab / natural diagenesis

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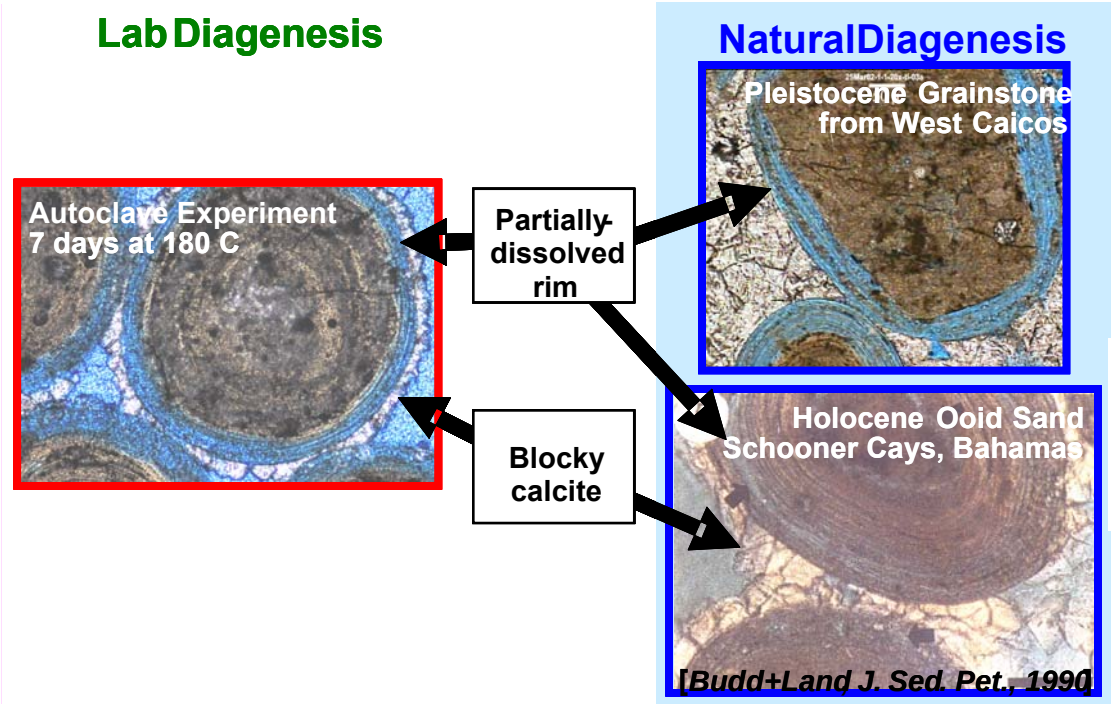
Morphology of lab diagenesis rock resembles natural samples



Cemented Ooid Grainstones, CT-scans

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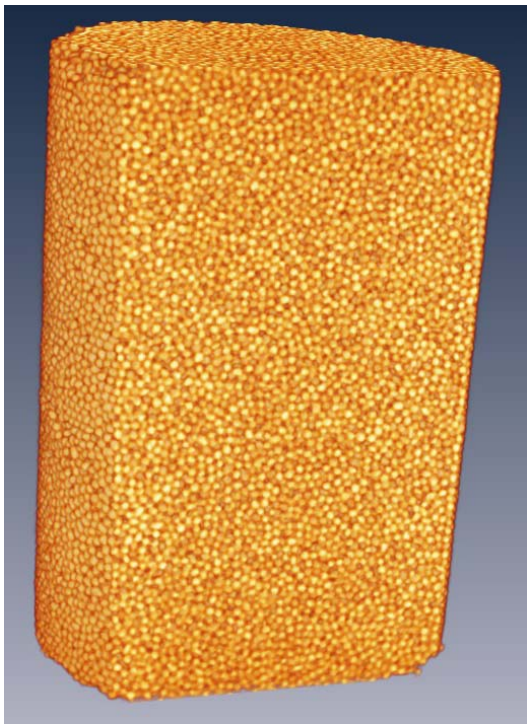
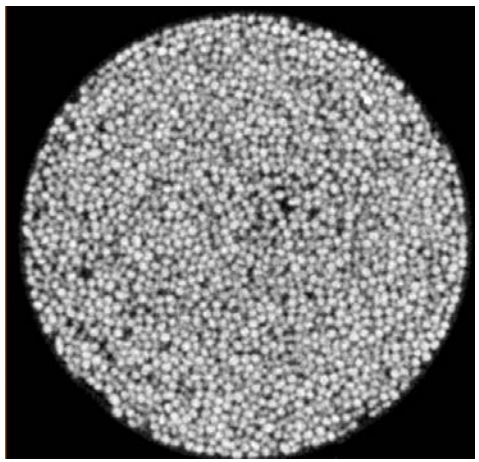
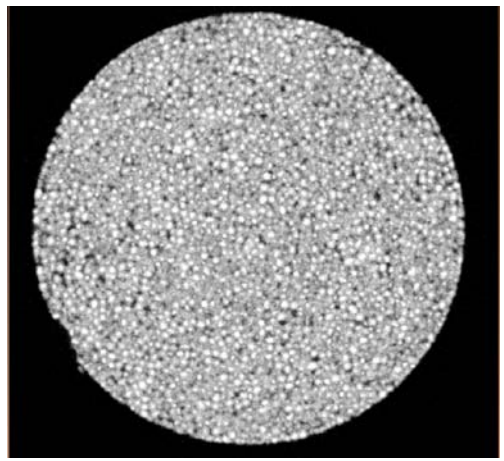
14 day

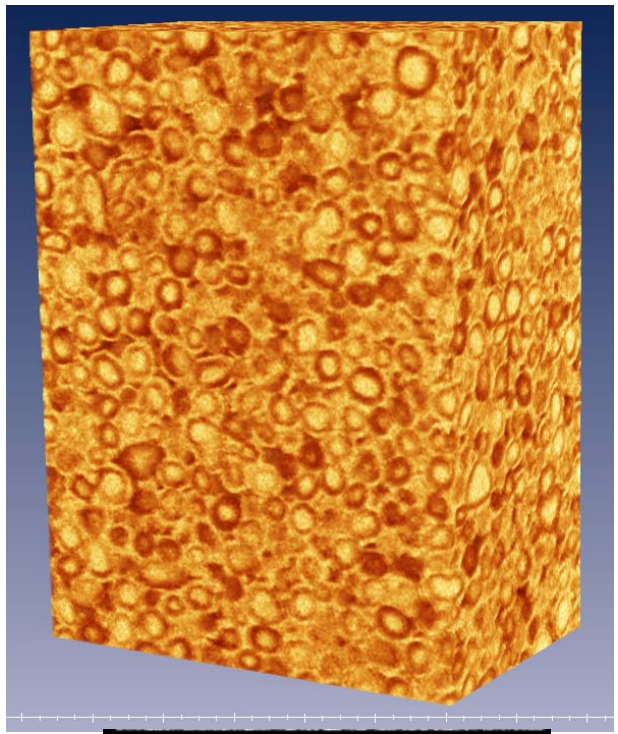


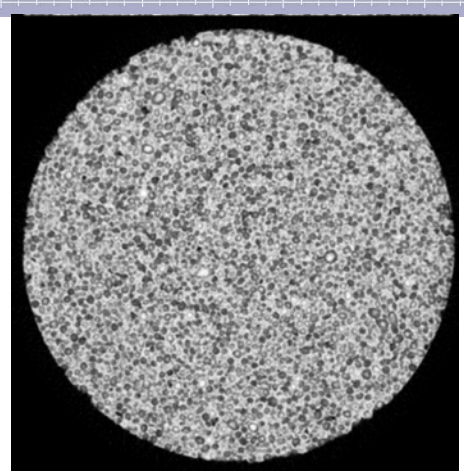


30 day



90 day





Ooid Thin Sections

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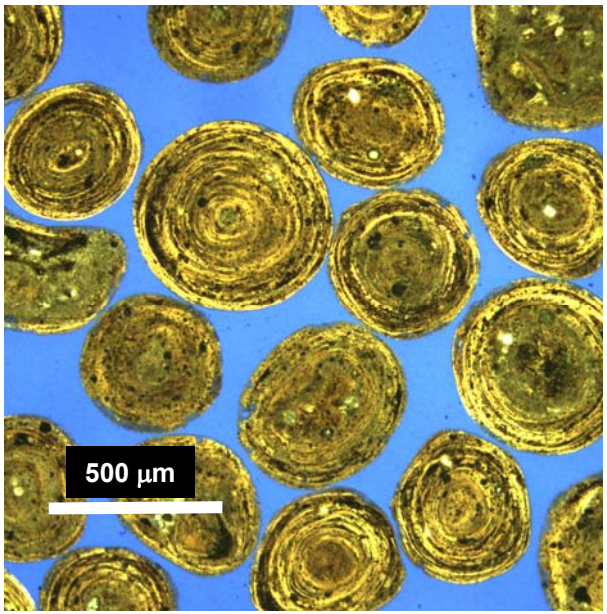
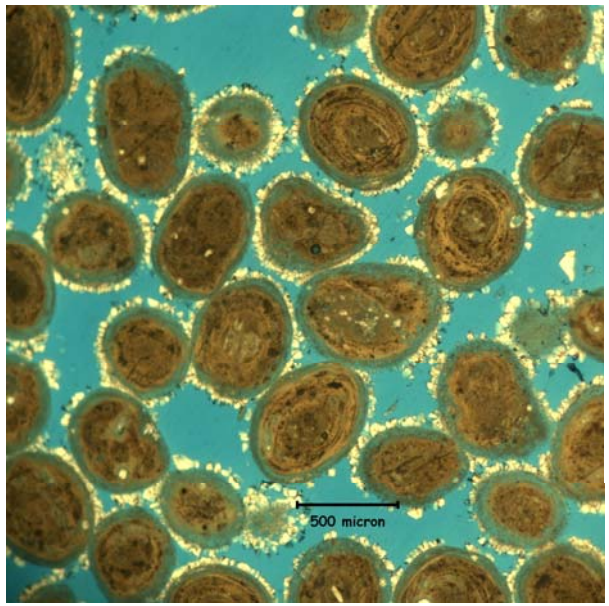
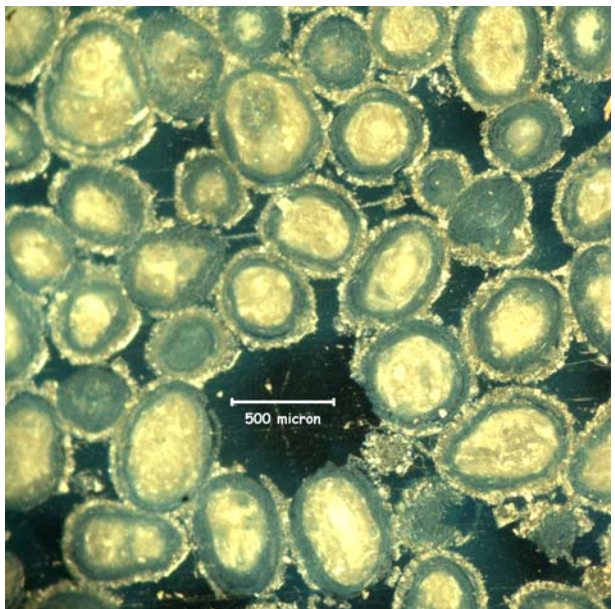
Fresh

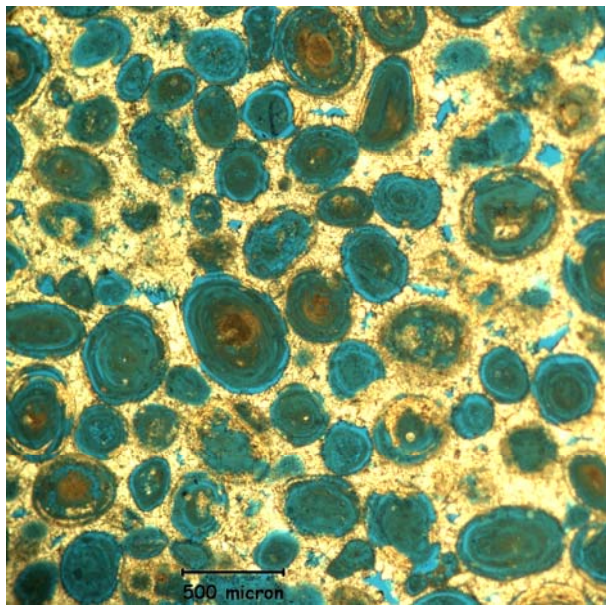




14 day

30 day





90 day

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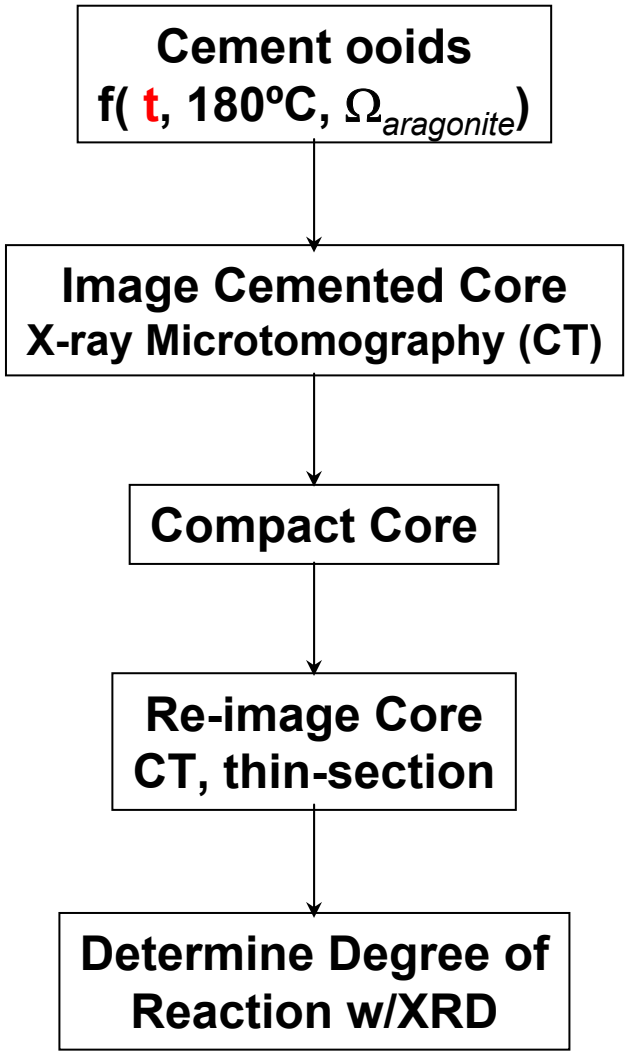
Uniaxial Strain Compaction Tests & Analyses

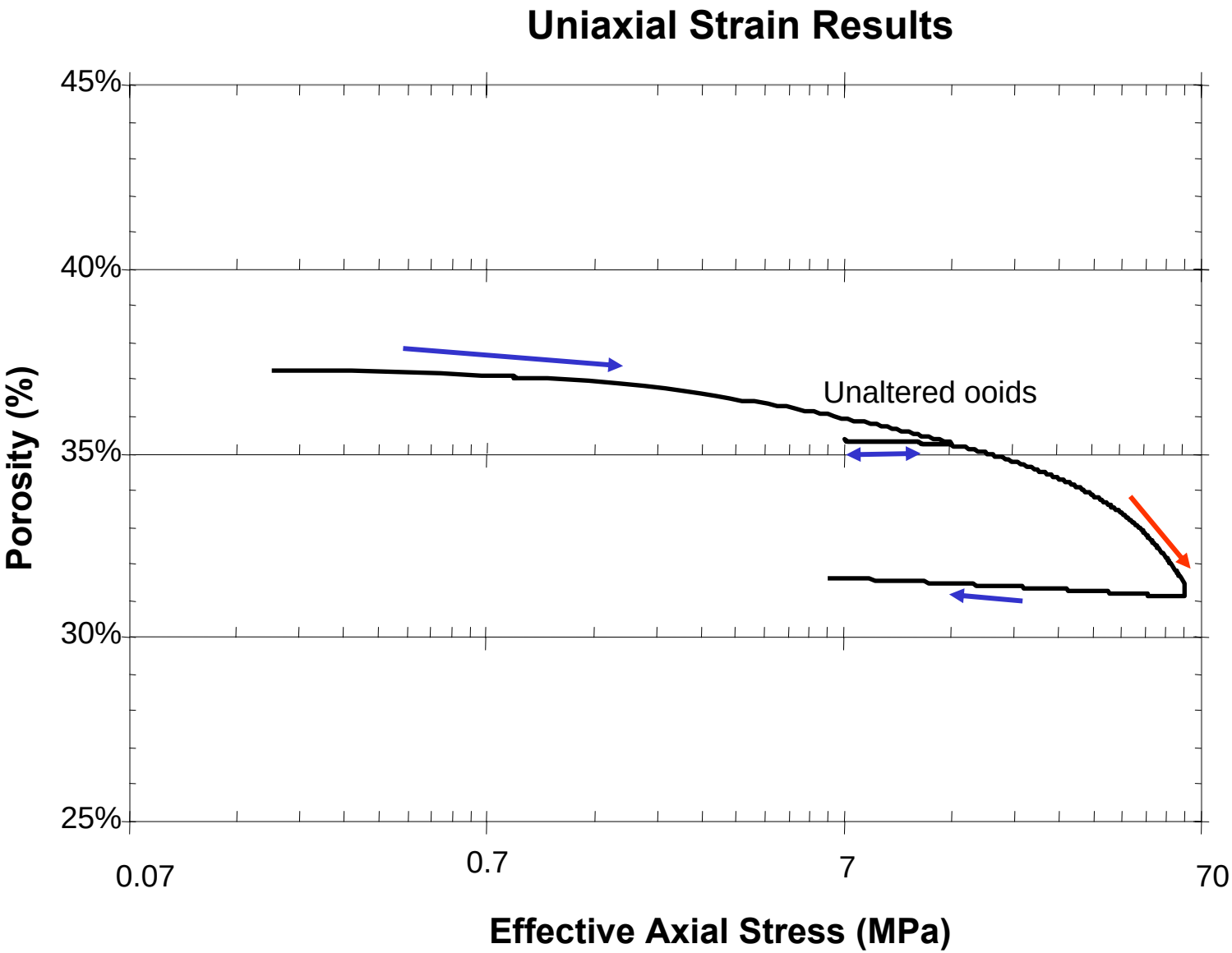
Synthetic Oolite Deformation & Analysis



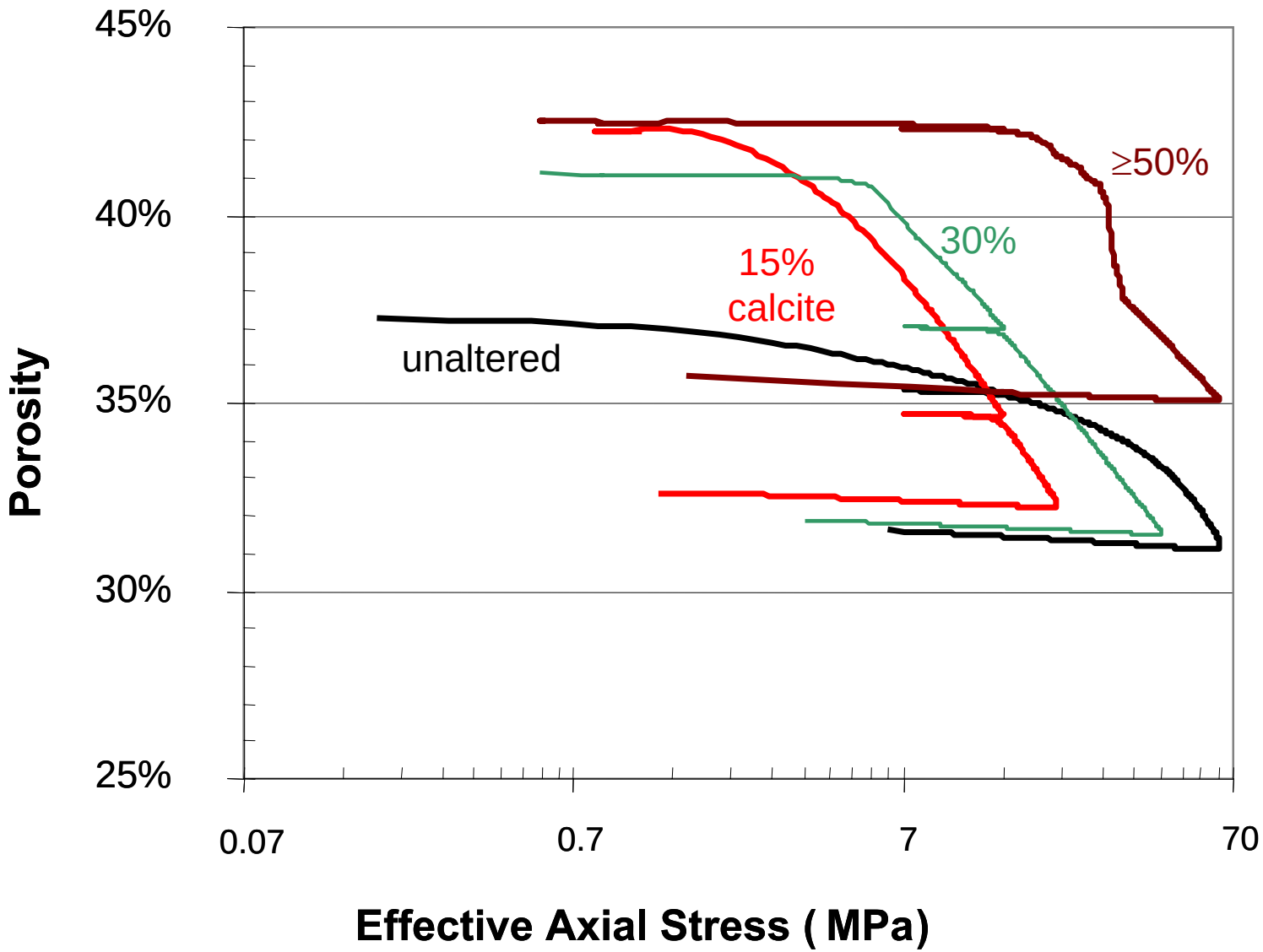
Samples Studied

time	*A→C reacted*
Unaltered ooids	
14 day	15%
30 day	30%
90 day	50%

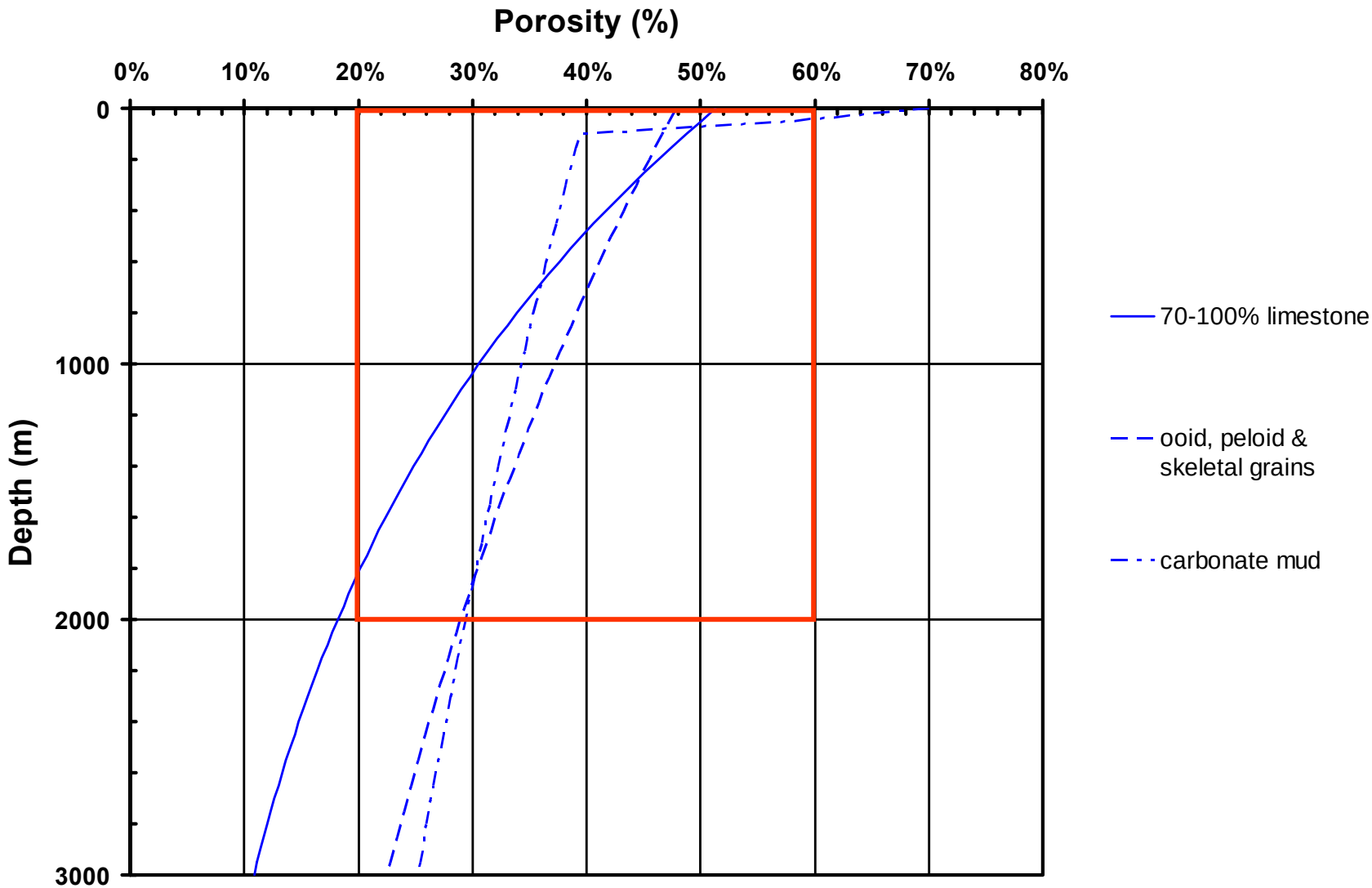
Compaction of Unaltered Aragonite Ooids



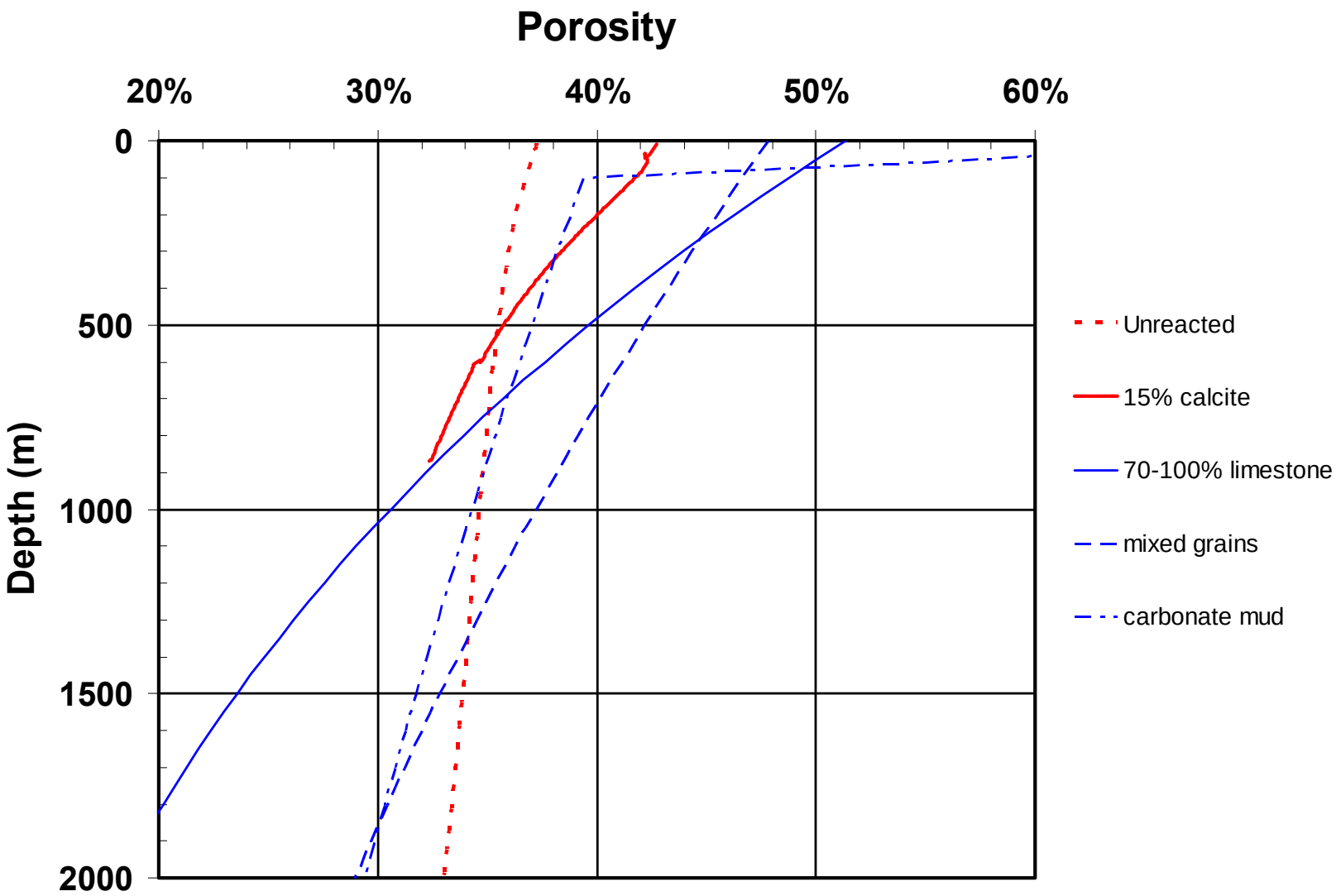
Uniaxial strain test results



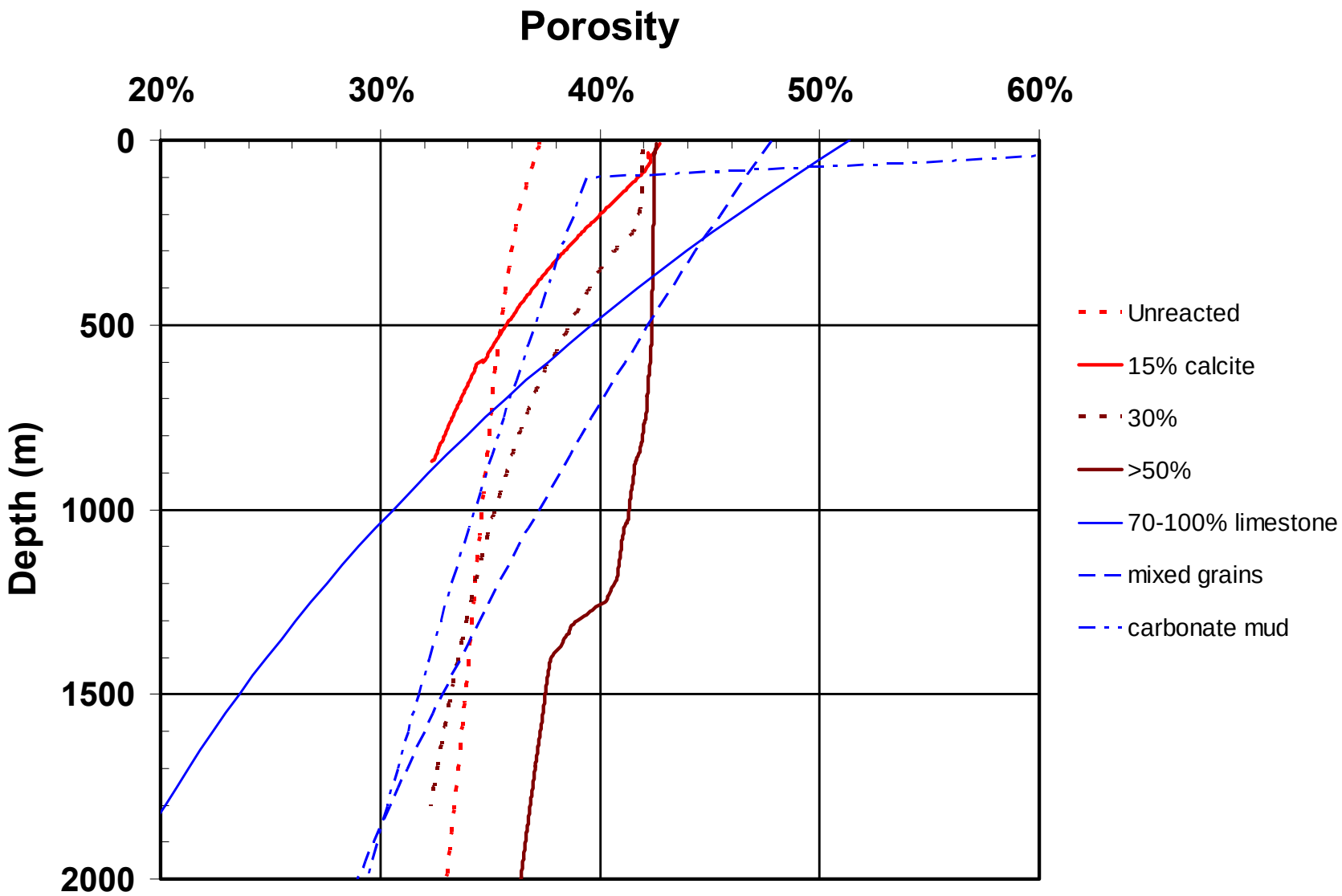
Published carbonate porosity profiles



Comparison to Published I

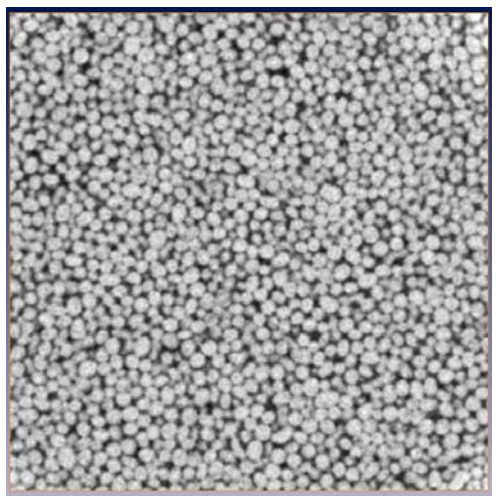


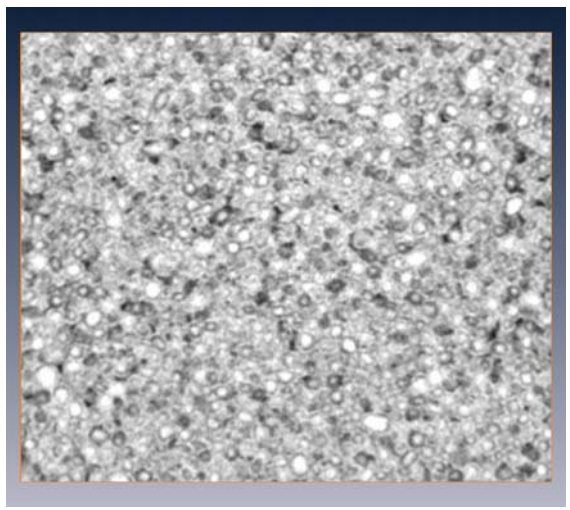
Comparison to Published II



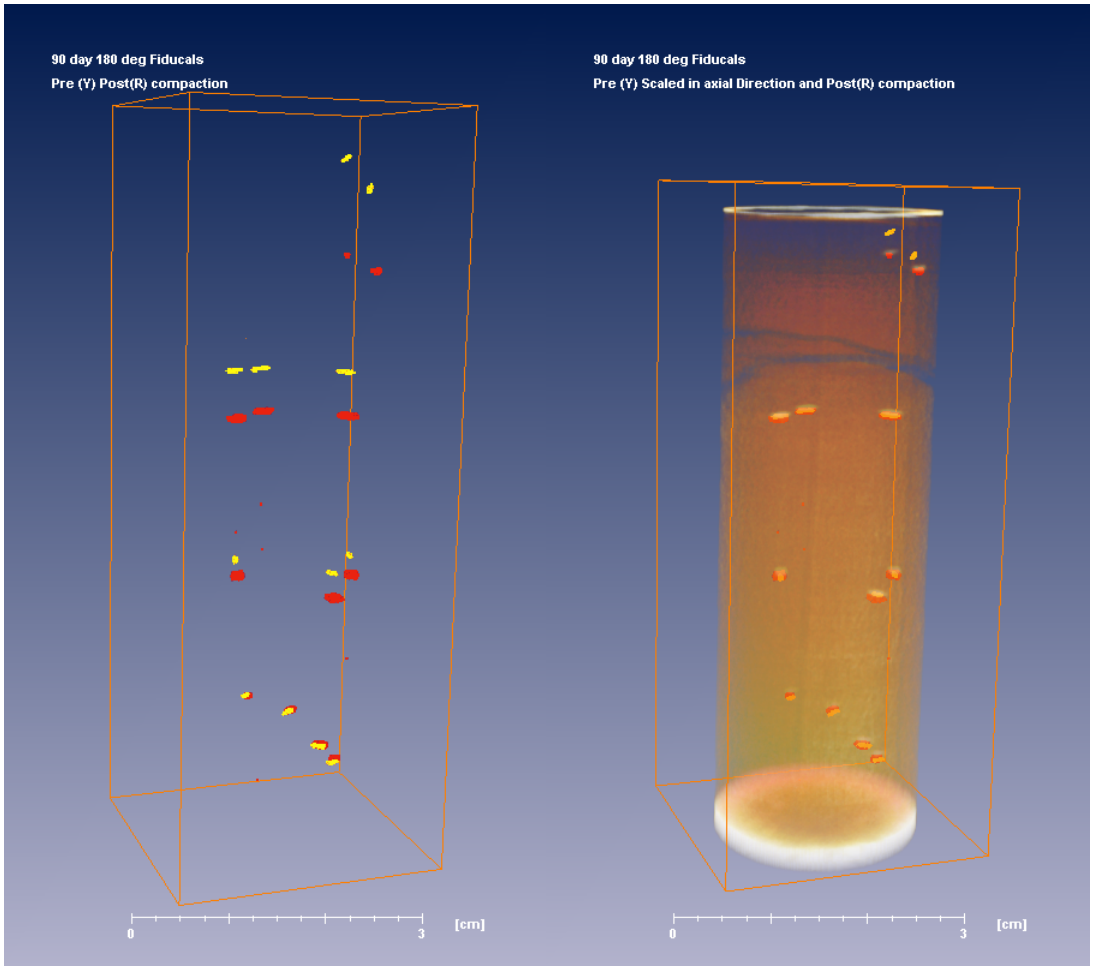
Quantitative X-ray Microtomography

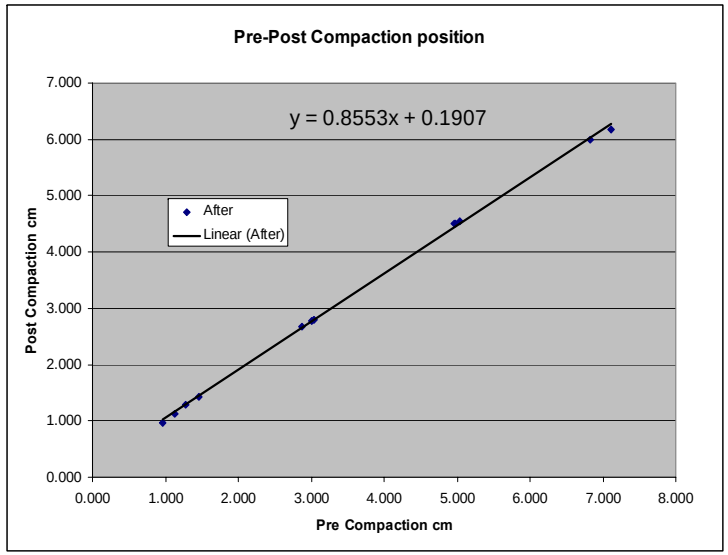
- **Registration (*pre versus post-compaction)***
  - Fiducial markers required to register pre and post compaction samples
    - + *AutoCorrelation Function analysis for unregistered samples*
    - + *2D visual inspection of local grain changes*
    - + *Potential for cross-correlation analysis for local changes*
- **Imaging difficulties**
  - Calibrate $CaCO_3$ X-ray opacity
  - Sample prep. techniques and pore fluid affect opacity
  - Damage in post-compaction cores





Fiducial Markers in ~50% calcite Sample



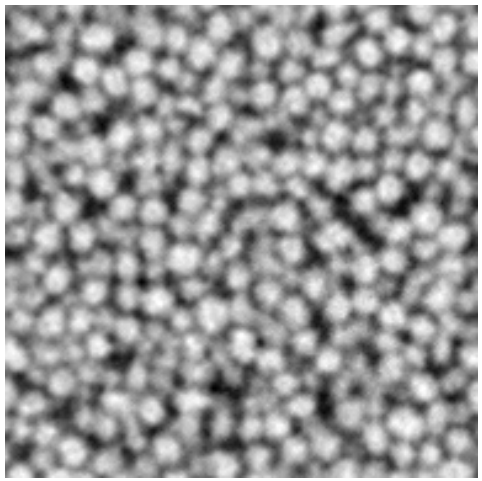


- **Initial marker position is difficult to control**
- **Simple Z scaling registers fiducial markers**
- **Compaction is homogeneous**

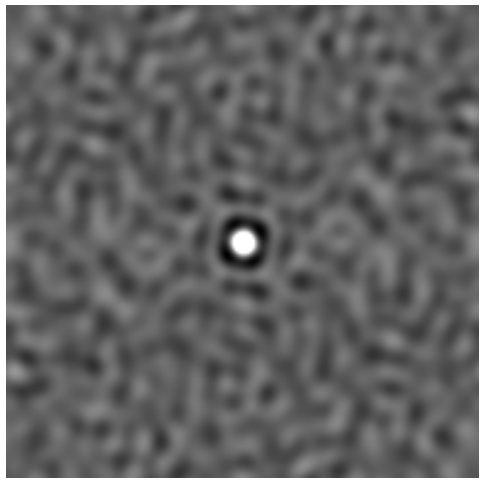
3D marker positions Pre-Compaction(Y) Post-Compaction(R)

3D marker positions after 1D axial image rescaling

3D AutoCorrelation Function



2D real space image of ooid grain pack



2D real space ACF of ooid grain pack

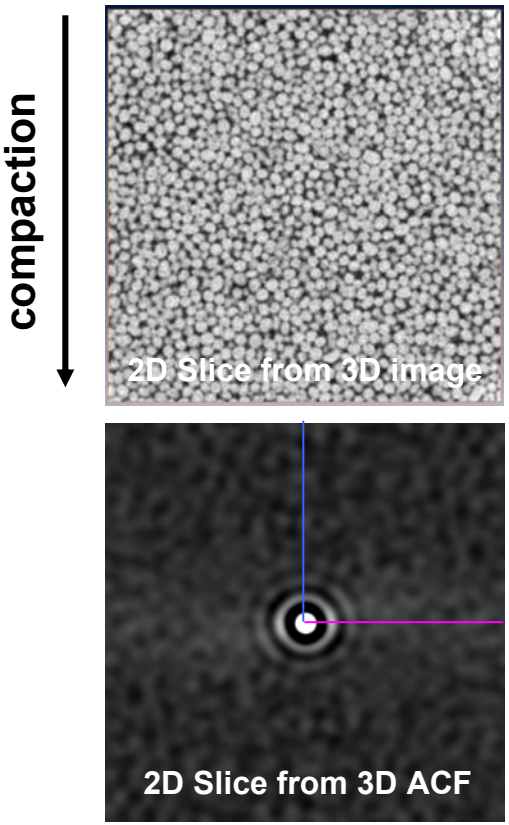
- **Computed using FFTs in 3D ACF(u,v,w) = F(u,v,w)F*(u,v,w)**
  - Measures probability that two points separated by ***r*** will both lie in the same phase in binarized pore-grain image (requires resolved grains)
  - Similar interpretation in calibrated (porosity) gray scale image
  - Qualitatively, 3D picture of the “averaged” grain environment

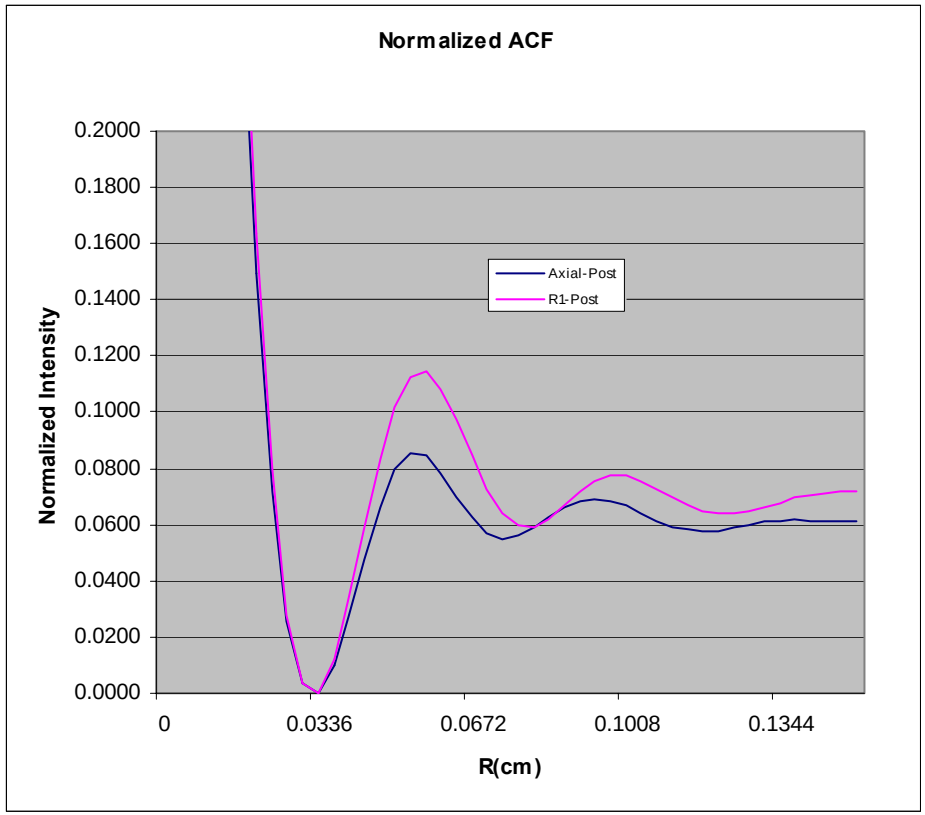
☹ **Images are not calibrated, but can make qualitative assessments.**

  - ACF arbitrarily rescaled to max = 1 and min = 0
  - Interpreted as the average density profile around a grain
  - Interpretation uncertainties in mixed diagenetic structures

☺ **It is not necessary to register images to compare the ACFs**

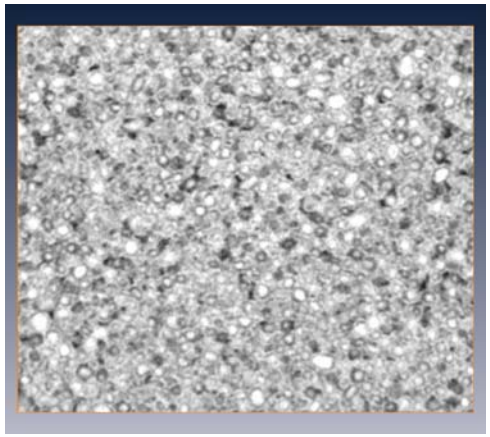
ACF Results, Compacted Fresh Ooids (17%)

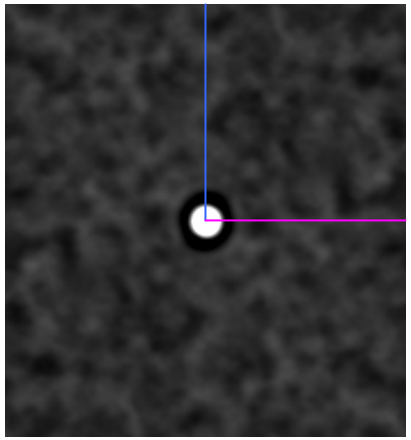


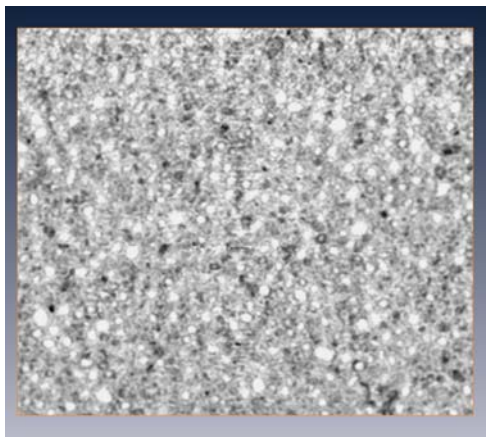


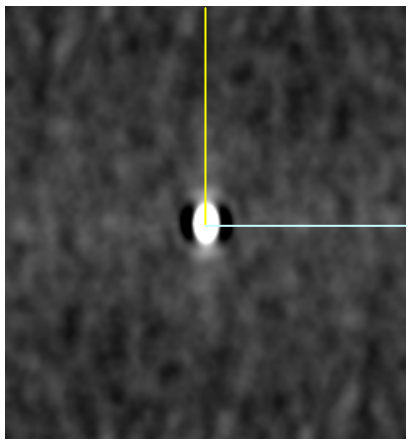
- Small change in axial compression direction.
  - Decrease in 1st neighbor distance from 570 to 540um
  - Slight decrease in intergranular contrast
- Interpretation
  - Some reordering of ooid grains to accommodate strain , little or no crushing or fines in pore space

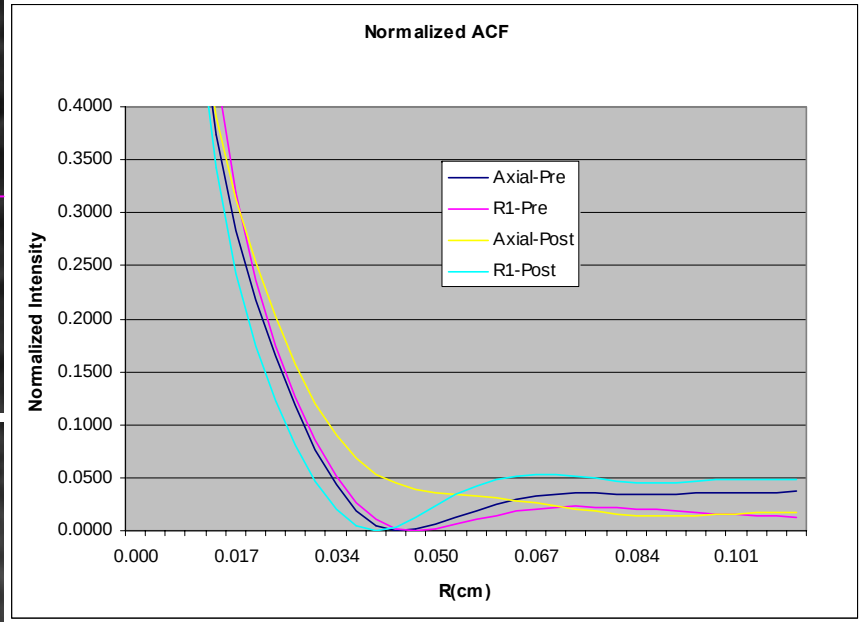
90 day: Compacted 15%





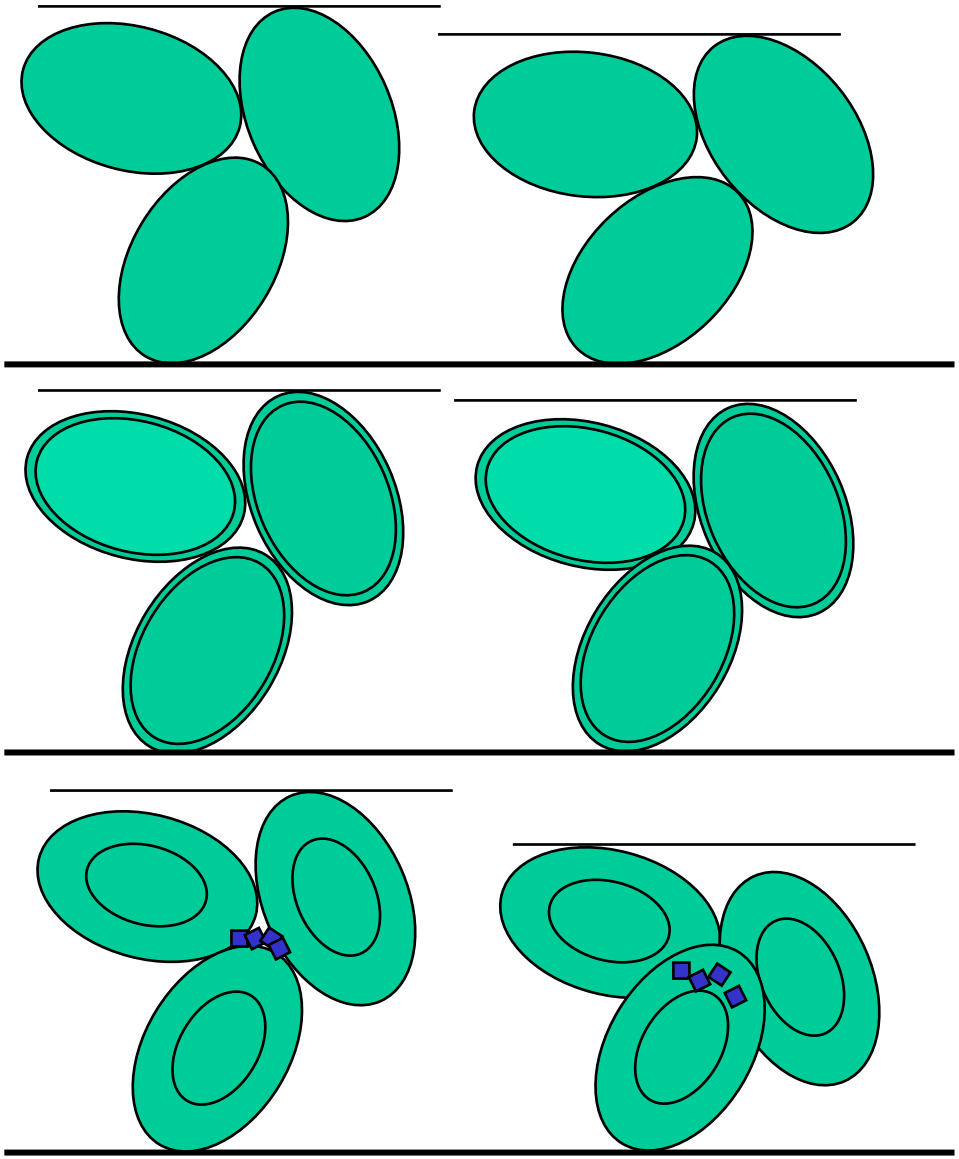






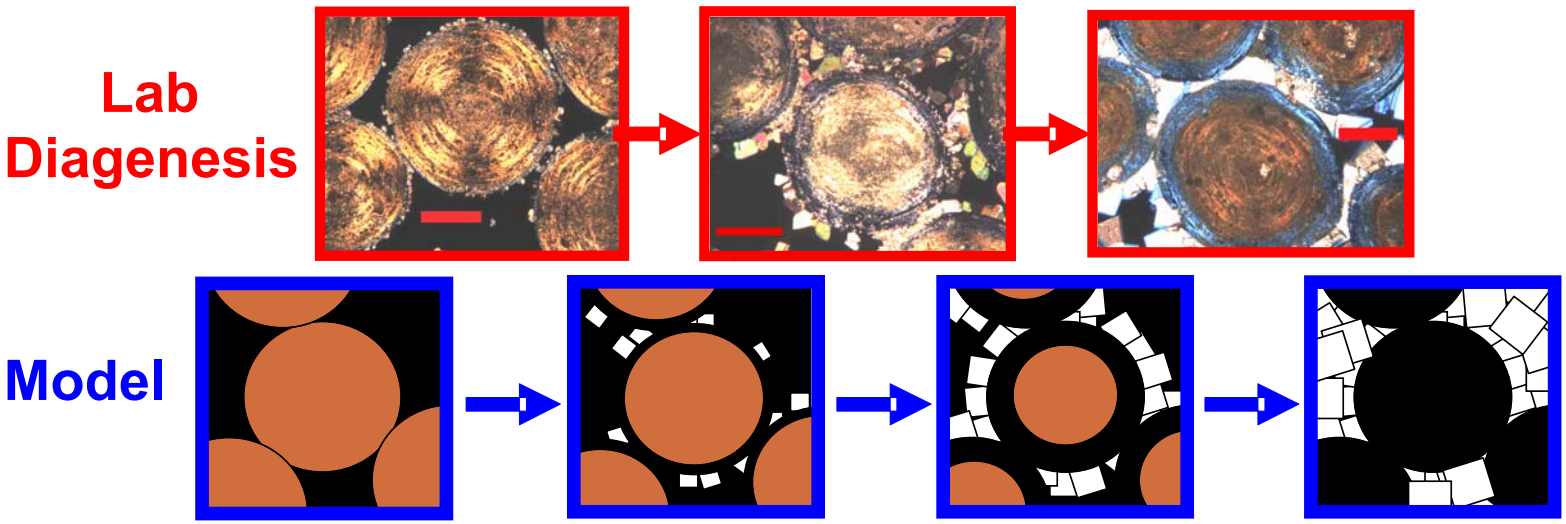
- Significant precompaction alteration of ooid structure. Weak 1st coordination shell.
- Post compaction decrease in radial 1st shell distance, slight increase in contrast
- Axial post compression suggests crushed dissolution products and cements.

Compaction Mechanism: *Based on Images*



- **No Conversion**
  - Stress accommodated by grain reorientation
- **Low Conversion**
  - Stress accommodated by compaction of dissolution rim
- **High conversion**
  - Stress accommodated by compaction of reacted rims and calcite cements
- **Full conversion?**
  - Stress also accommodated by calcite framework crushing?

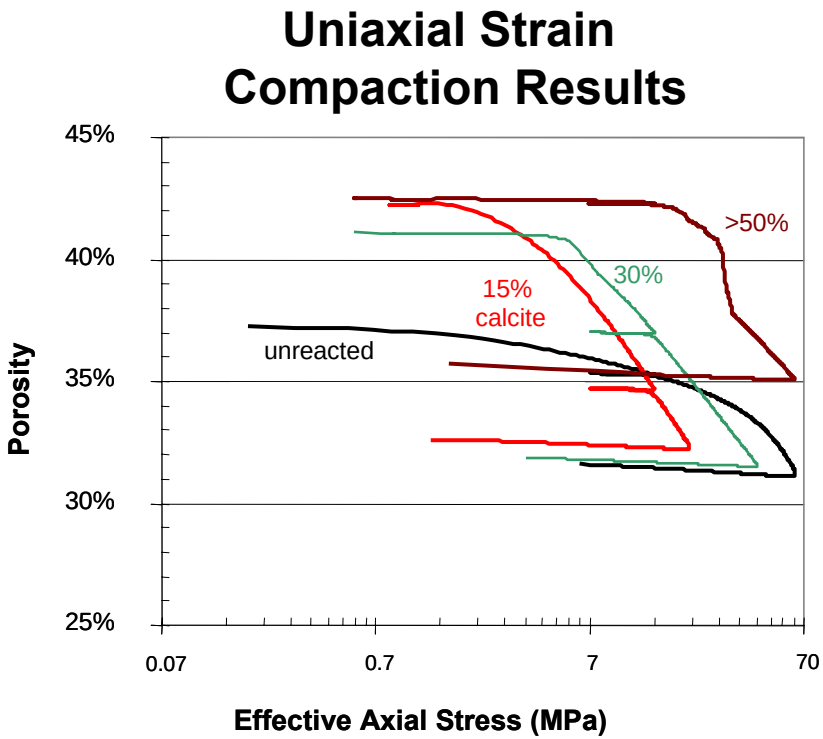
Summary I: Frabricated Poldic Porosity

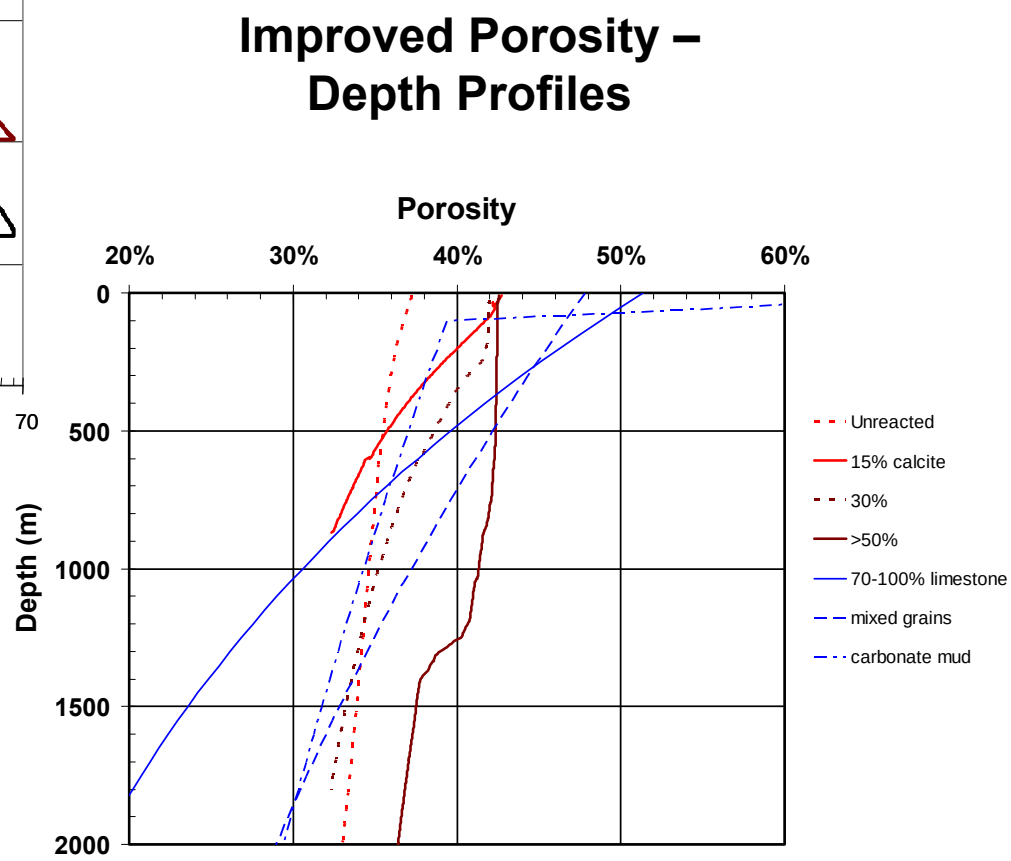


- Local, pore-scale, simultaneous dissolution and precipitation
- Aragonite partially dissolves from outer surface inward
- Calcite grows on outer surface
- Rim: Aragonite nonoparticles dissolve first, leaving needles
- Framework of leftover aragonite needles allows structural inversion

Synthesizing diagenetic rocks in the laboratory allows systematic, quantitative investigation

Summary II: Evolution of Mechanical Behavior





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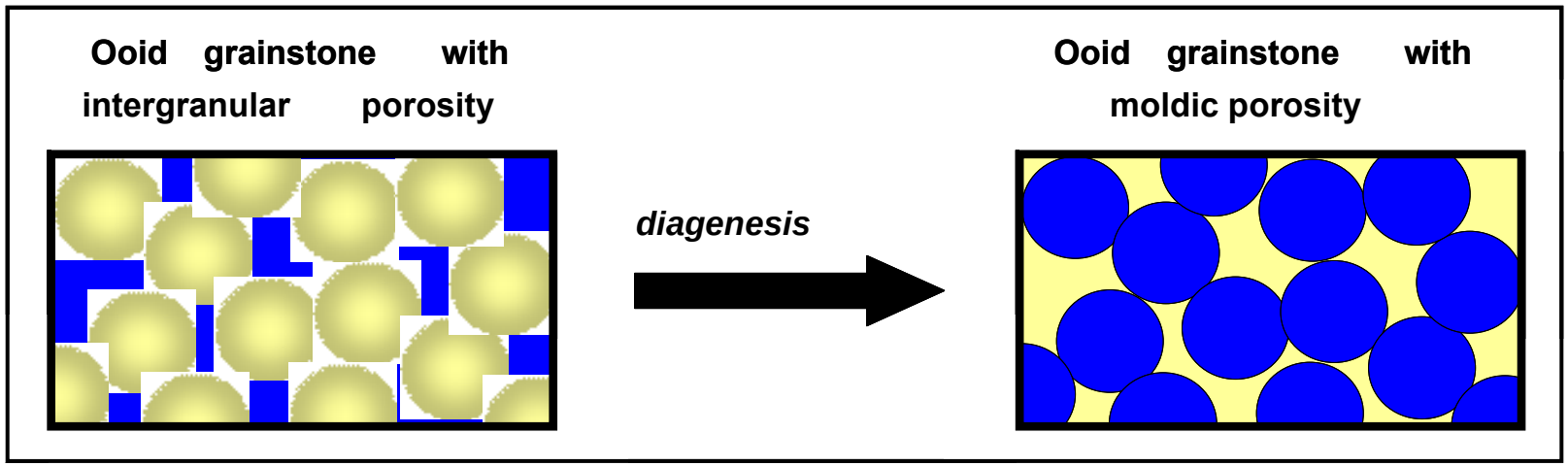
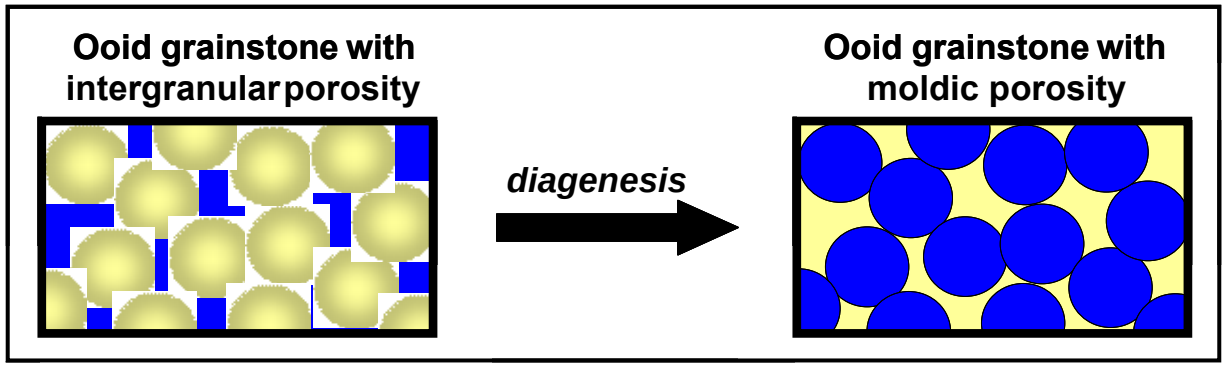
Students?

Help!?

Hint…

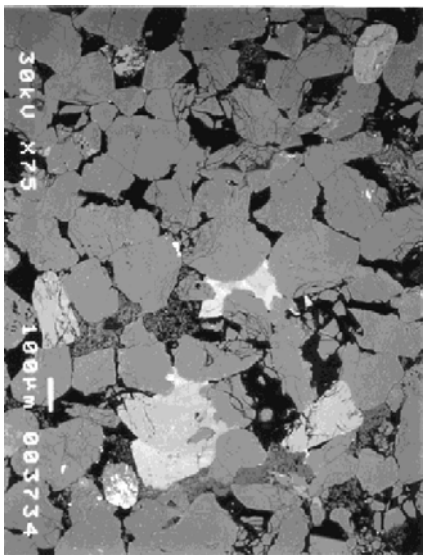

Ooid grainstone with intergranular porosity
diagenesis
Ooid grainstone with moldic porosity

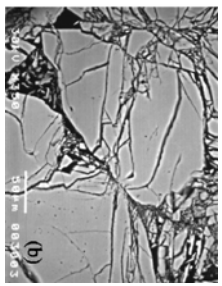
Summary III: Texture / Mechanical Evolution



Compaction of Granular vs. Foam Textures

Berea sandstone (P_{eff} =10 MPa)



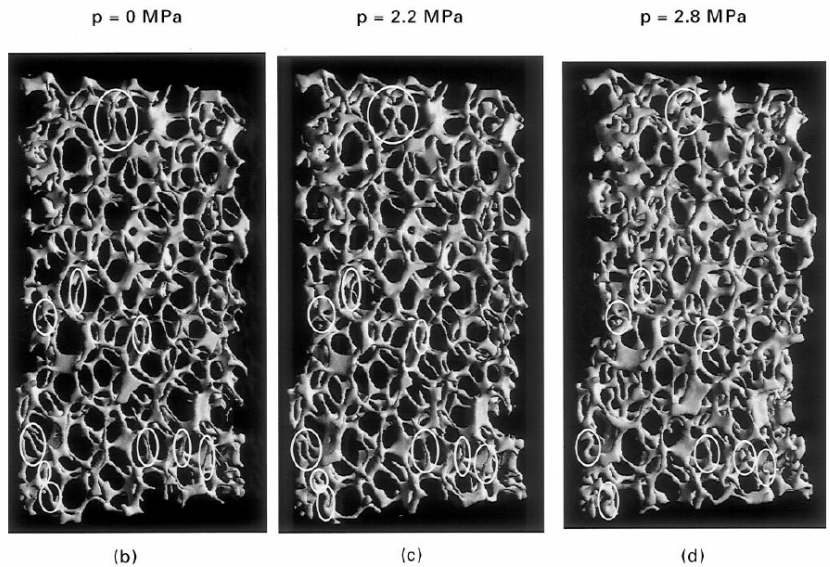


σ_1

Borrowed from T-f Wong

Menéndez, Zhu & Wong (1996)

Metal Foam, Micro-CT images (hydrostatic pressure)



Gioux et al. (2000)

What Next?

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- **Rock Synthesis**
  - Move beyond moldic porosity to other pore/rock types?
    - + *Other key carbonate reservoir types*
    - + *Cements in siliciclastics*
- **Geomechanical tests:**
  - Explore other stress paths & physical properties (e.g., AE, V_p & V_s, electrical…)
  - **Evolution of permeability**
- **X-ray Microtomography analysis**
  - Continue to improve techniques
  - Quantify grain properties
    - + *Grain type and degree of conversion*
    - + *Identify importance to compaction behavior*
  - Quantify Rock Deformation
    - + *E.g. non-uniform compaction: track local grain displacements and morphology changes using cross correlation*
- **Seek more direct link to grain-scale geomechanics modeling**


Thank You!
(http://landsat.org)